

THE WEATHER AND CIRCULATION OF SEPTEMBER 1957¹

Including a Discussion of Tropical Storm Activity

EMANUEL M. BALLENZWEIG

Extended Forecast Section U. S. Weather Bureau Washington 25, D. C.

1. COMPARISON WITH THE SUMMER MONTHS

The weather and circulation of the past summer was marked by extreme heterogeneity. The month of June was characterized by a mean trough through the central part of the United States with ridges along each coast [6]. A marked reversal in circulation characteristics took place between June and July [5] as a pattern more typical of summer emerged with a trough off each coast and a ridge over the Great Plains. The sharp circulation reversal from June to July was followed by strong persistence from July to August at middle latitudes of the Western Hemisphere [4].

The circulation experienced yet another oscillation in its transition from August to September. The planetary wave train became remarkably akin to that of June 1957 [6], with a trough again in the middle of the United States and the coastal troughs of July and August supplanted by ridges (fig. 1). The reappearance of the mid-continental trough was suggested during the latter half of August (15-day mean, not shown), when the east coast trough fractured, with the southern portion retrograding toward the lower Mississippi Valley.

Despite the large changes in hemispheric circulation observed from August to September (fig. 2A), blocking was still an important feature of the circulation. The block that had been dominant in the western Canada-Alaska area for the previous three months became a strong ridge along the west coast of Canada, appearing as a closed High on many of the 5-day mean maps (fig. 3). Blocking re-emerged in the Greenland area and in the Bering Sea, where 700-mb. heights were 320 feet above normal and sea level pressures (Chart XI, inset) 7 mb. above normal. The high latitude block over Siberia in August [4] moved southwestward into western Siberia, and the deep polar vortex of August filled greatly as the polar region became a seat of above normal heights.

Persistence from August to September, while climatologically not quite as marked as from July to August [7], is usually much stronger than it was this year (table 1). The -0.29 lag correlation of 700-mb. height anomalies over the United States is an indication of the reversal that took place. The lack of persistence in the circulation was reflected in large-scale changes in temperature

and precipitation. Only 56 of 100 stations in the United States changed temperature by one class or less compared with a normal of 72; similarly, fewer than normal stations (20 instead of 35) remained in the same precipitation class (last line of table 1). Part of the associated reversal in weather regime (figs. 2B and 2C) can be interpreted in terms of the changes in 700-mb. height anomalies from August to September (fig. 2A).

2. MONTHLY MEAN CIRCULATION AND WEATHER

The fairly well-defined temperature and precipitation patterns for the month of September (Charts I-B, II, and III-B) can be related quite well to the monthly 700-mb. height and height anomaly patterns (fig. 1), despite the changes in these patterns which took place during the month (section 3). Temperatures as much as 5° F. above normal occurred in the Pacific Northwest and along the California coast under anticyclonic conditions, above normal heights, and abundant sunshine (Chart VII). The warm temperatures in the Pacific Northwest during September represented an extremely sharp reversal from the cool weather experienced there during August (fig. 2B). This warmth was a consequence of upper-level ridge development along the coast (fig. 2A) and frequent anticyclonic passages in the vicinity of the Rockies (Chart IX) which kept the Northwest mainly in dry southerly flow at sea level. Warming was also experienced along the east coast, largely as a result of anticyclonic conditions off the coast (figs. 1 and 2A).

The area from the Rockies to the Appalachians was cool (Chart I-B) as a consequence of frequent intrusions of polar Canadian anticyclones (Chart IX). These anticyclones were steered rather well by the mean 700-mb. flow from the northwest. This area was one of below normal 700-mb. heights and cyclonic flow at 700 mb. Northerly anomalous flow from the Rockies to the Missis-

TABLE 1.—Persistence measures of monthly mean anomalies in the United States from August to September

	1957	Normal*	Random
700-mb. height (lag correlation).....	-0.29	$+0.33$	0.00
Temperature (0 or 1 class change, percent).....	56	72	60
Precipitation (0 class change, percent).....	20	35	33

*Normal persistence measures of 700-mb. height based on 1933-1950 data, temperature on 1942-1954 data, and precipitation on 1942-1950 data.

¹ See Charts I-XVII following p. 328 for analyzed climatological data for the month.

least amount for that period in 125 years. A similar record was set in Boston, Mass., which had its driest 9 months in 140 years. The desiccation in parts of the Pacific Northwest and through the Plateau States (Albuquerque reported only a trace of rain for September) was the result of anticyclonic circulation and dry northerly anomalous flow aloft.

Temperatures along the California coast were warm despite record precipitation amounts recorded in many cities. The weather was prevailing fair until the last few days of the month when a deep upper-level trough off the northern California coast brought moderate to heavy thundershowers with some hail to this area.

3. TRANSITION WITHIN THE MONTH

Unlike the relatively stationary wave pattern of July and August, September was characterized by change during the month (fig. 3). The first 3 weeks showed a steady retrogression of the major features of the circulation, followed by a rapid reversal in the fourth week. Concomitant with these permutations were changes in the temperature and precipitation regimes (figs. 4 and 5).

FIRST WEEK

In general, weekly temperatures averaged above normal from the Divide westward and from the Appalachians eastward, with below normal temperatures reported in the rest of the Nation (fig. 4A). Under a strong ridge (fig. 3A) temperature departures as large as $+6^{\circ}$ to $+7^{\circ}$ F. occurred in Montana and inland portions of southern California. Record maximum temperatures were observed in Helena, Mont. (92° F.), Las Vegas, Nev. (108° F.), and Red Bluff, Calif. (109° F. on Sept. 6 and 7). Las Vegas had 7 consecutive days with the temperature reaching or exceeding 100° F. Temperatures were above normal along the east coast as southerly flow prevailed east of the trough in the Mississippi Valley (fig. 3A). Record maximum temperatures for the date were established in Charlotte, N. C. (100° F.) and Columbia, S. C. (99° F.) on September 1.

Heavy precipitation in the extreme Pacific Northwest was the consequence of anomalous onshore flow of maritime Pacific air. A storm which developed in South Dakota on September 1 (Chart X) deepened rapidly on the 2d and 3d, and moved across the Northern Plains, accounting for the precipitation observed in that area during the week and, in fact, for a large share of the monthly total there. Its passage was followed by a series of cold outbreaks into the United States, with freezing temperatures reported in northern and central lowlands of Wisconsin on the 5th and subsequent dates and a reading as low as 23° F. in Cranmoor. New record minima were observed in such widely scattered cities as Erie, Pa., San Antonio, Tex., Indianapolis, Ind., and Grand Junction, Colo.

Perhaps the most important weather news of the month was hurricane Carrie which formed on September 2 and was in the headlines until its demise near western Europe

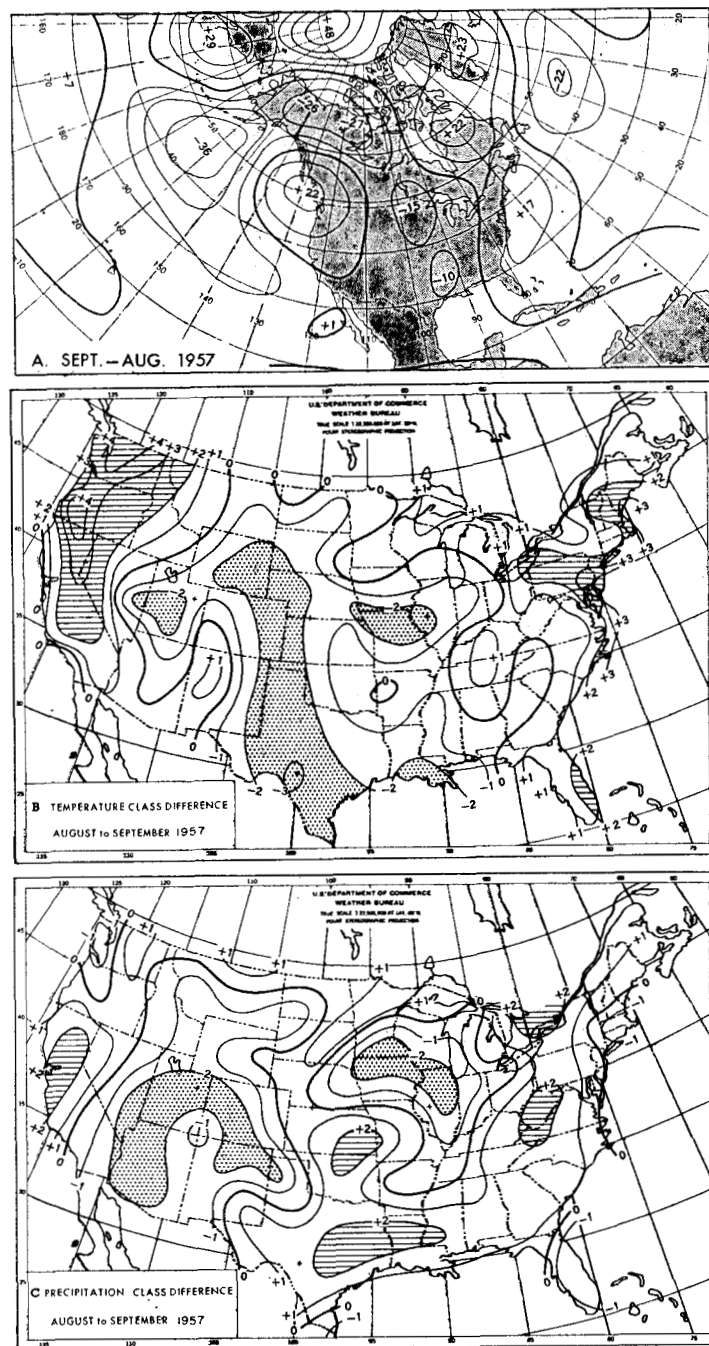


FIGURE 2.—Changes in monthly mean 700-mb. height departures from normal, August to September 1957. The isolines of anomalous height change (A) are drawn at 100-ft. intervals, with the zero line heavier and the centers labeled in tens of feet. A large reversal took place from August to September, as reflected in the number of classes the anomaly of temperature (B) and precipitation (C) changed. Increased values are considered positive and decreased values negative. Areas with increases of two or more classes are cross-hatched; areas with decreases of two or more classes are stippled.

on September 25 (fig. 6). More will be said about its development and subsequent motion in sections 4 and 5. Of more consequence to the weather of the United States was a weak tropical storm, Debbie, which formed in the central Gulf of Mexico on September 7 and moved north-

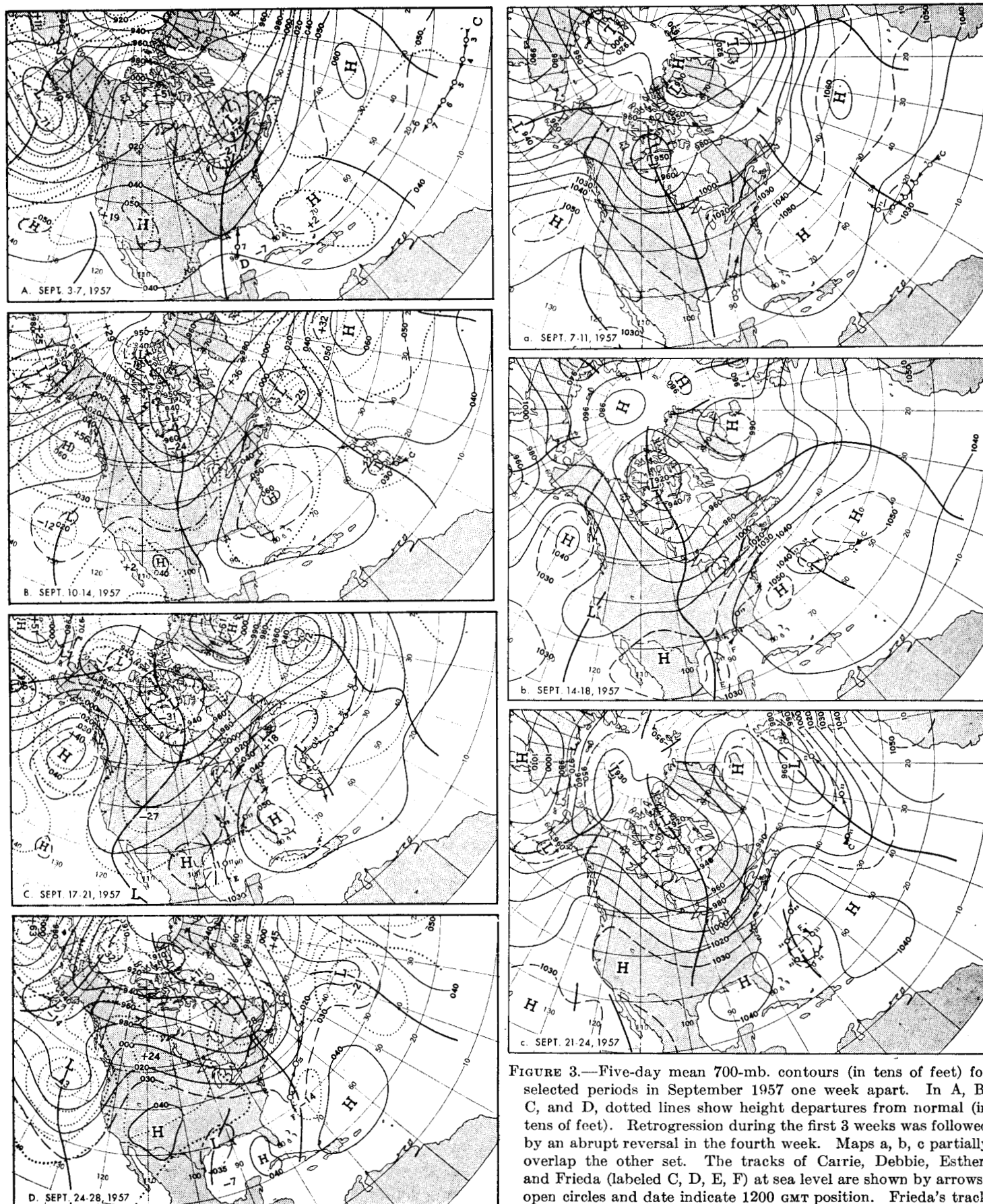


FIGURE 3.—Five-day mean 700-mb. contours (in tens of feet) for selected periods in September 1957 one week apart. In A, B, C, and D, dotted lines show height departures from normal (in tens of feet). Retrogression during the first 3 weeks was followed by an abrupt reversal in the fourth week. Maps a, b, c partially overlap the other set. The tracks of Carrie, Debbie, Esther, and Frieda (labeled C, D, E, F) at sea level are shown by arrows; open circles and date indicate 1200 GMT position. Frieda's track from the 16th to the 20th is hypothetical.

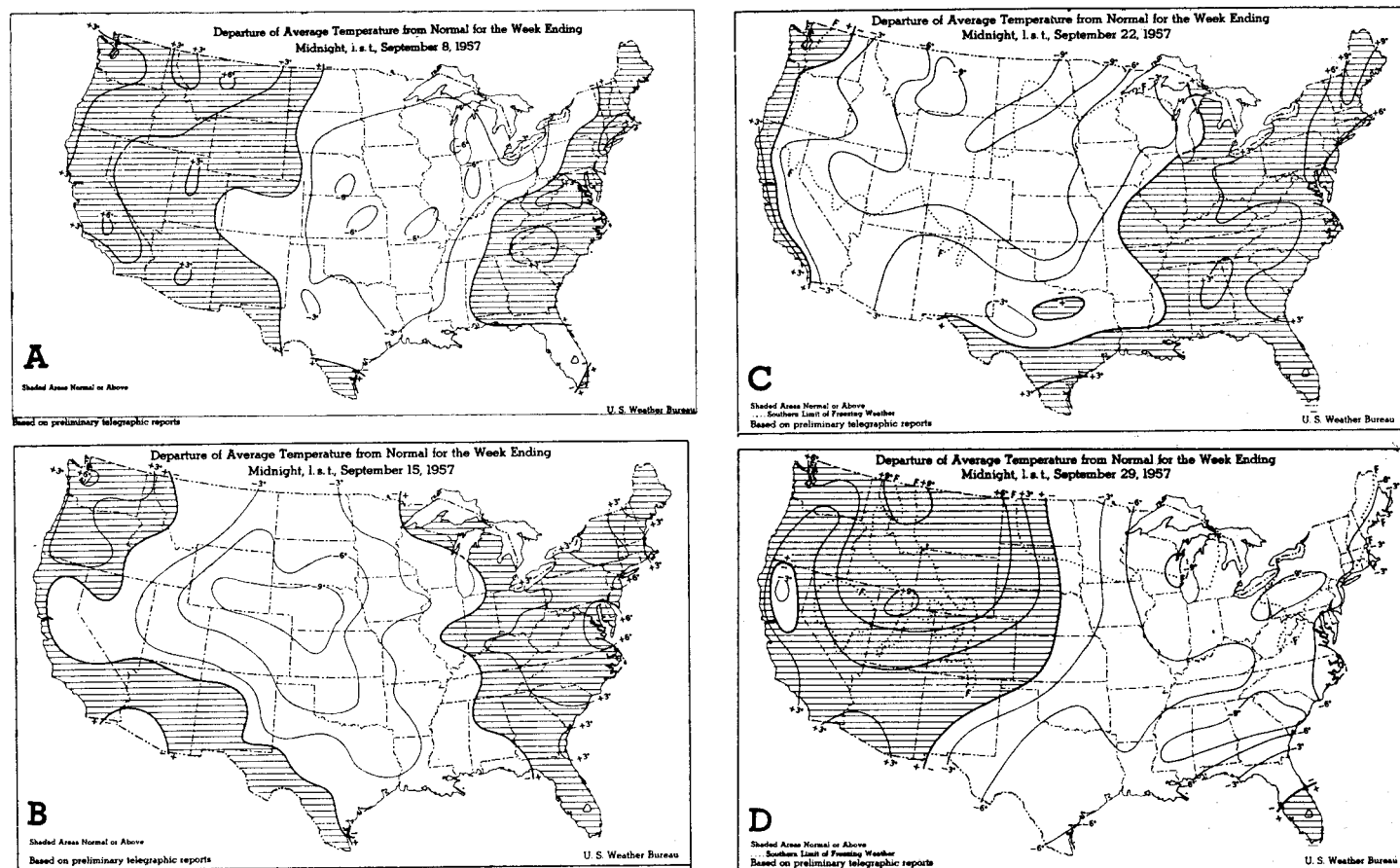


FIGURE 4.—Departure of average surface temperature from normal ($^{\circ}\text{F}.$) for weeks in September 1957, centered on the 5-day mean periods shown in the left column of figure 3, and ending (A) September 8, (B) September 15, (C) September 22, and (D) September 29. Retrogression of the pattern is discernible through the first three weeks, followed by a reversal. (From *Weekly Weather and Crop Bulletin, National Summary*, vol. XLIV, Nos. 36–39, Sept. 9, 16, 23, and 30, 1957.)

eastward through northwestern Florida, southeastern Alabama, and Georgia. No casualties or severe damage were reported as the highest winds were about 40 m.p.h. with gusts up to 50 m.p.h. along the northwestern coast of Florida. Some flooding was reported due to heavy rain and high tides. Tides were as high as 4 feet above normal at the Panacea Coast Guard Station in northwestern Florida, and stations in that area had rain in excess of 9 inches. In general the precipitation associated with Debbie was about 2–4 inches, extending over an area from Florida to North Carolina (fig. 5A). The isohyetal pattern was typical of tropical storms, with the heaviest rainfall to the right of the storm's path.

SECOND WEEK

The retrogression that took place from the first to the second week is manifest in the 700-mb. map centered on the middle of the second week (fig. 3B) and the associated weather (figs. 4B and 5B), compared with that of the preceding week (figs. 3A, 4A, and 5A).

Above normal temperatures spread westward to the Ohio Valley, with the warmest temperatures along the east coast (fig. 4B). Temperatures were $7^{\circ}\text{F}.$ above

normal in Baltimore, Md.; and other cities along the mid-Atlantic seaboard reported temperature anomalies in excess of $+5^{\circ}$. This area was under the influence of a strong ridge (with heights 200 feet above normal) and abundant sunshine. Record high temperatures were set in Boston, Mass., Providence, R. I., and New Haven, Conn.

The polar outbreaks continued over the central interior United States as the boundary of below normal temperatures retrograded to the west of the Rockies. Temperatures for the week averaged $10^{\circ}\text{F}.$ below normal at Cheyenne, Wyo., Grand Island, and North Platte, Nebr. As the ridge in the west retrograded, the area of above normal temperatures diminished there. The largest temperature departure reported was $+6^{\circ}\text{F}.$ at Seattle, which had its highest temperature of the year on September 13.

West of the Continental Divide another rainless week continued the dry weather regime (fig. 5B). In Washington and Oregon dry weather combined with above normal temperatures and low relative humidity to intensify the extreme fire hazard, and logging operations were suspended in western Washington. Very little rain fell

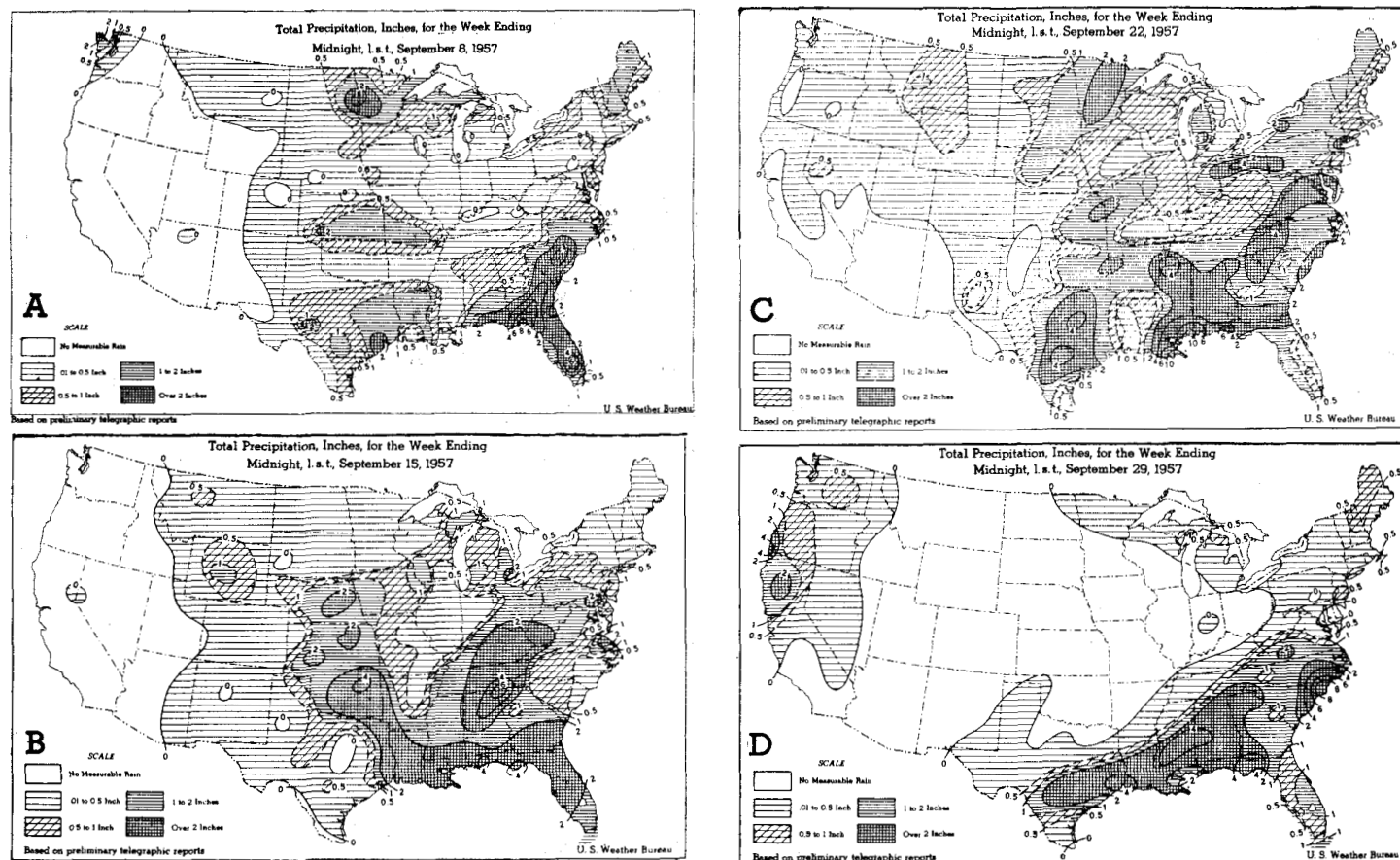


FIGURE 5.—Total precipitation (inches) for the same weeks and from the same source shown in figure 4. Heavy rain fell along the Gulf coast and in parts of the Southeast each week.

anywhere to the west of the United States trough, except for light precipitation in the Rockies, including snow in southern Wyoming and a 5-inch fall in Colorado. Moderate to heavy rains fell over the central Great Plains in an area of cyclonic circulation, with amounts exceeding 3 inches in Nebraska and Kansas. Heavy rain continued along the Gulf coast as deep tropical moisture was advected northward. A tongue of heavy precipitation extended northward on the windward side of the Appalachians into the Ohio Valley. More than 7 inches fell in Chattanooga, Tenn., partly in response to the remnants of Debbie. Thundershowers produced some small pockets of heavy rain along the mid-Atlantic coast. But a large portion of this area, especially New England, experienced light precipitation under anticyclonic circulation.

THIRD WEEK

Further retrogression of the circulation features, and the attendant weather anomalies, took place from the second to the third week of the month (figs. 3C, 4C, 5C). The mid-continental trough sheared and joined the California trough as the latter intensified. The block in the Gulf of Alaska weakened as it moved westward. The east coast ridge also weakened.

The eastern third of the United States had continued hot weather (fig. 4C), with new maximum temperature

records set in Schenectady, N. Y., on the 21st and 22d. Temperature anomalies were most extreme in the Northeast, where a departure of $+10^{\circ}$ F. was observed in Caribou, Maine, $+9^{\circ}$ F. in Concord, N. H., and $+8^{\circ}$ F. in Baltimore, Md. Precipitation was generally abundant in the eastern half of the Nation in broad southerly flow ahead of the mean trough (fig. 5C).

Tropical storm Esther entered the mainland over southeastern Louisiana (fig. 6), with winds of 50 m. p. h. and gusts up to 75 m. p. h. It was the third tropical storm this season to make landfall on the same narrow strip of coastline. Esther was responsible for torrential rains which fell in squalls northeast of its center. Rain in excess of 10 inches was not uncommon, and as much as 18 inches was recorded at Quarantine, La. Highest tides ranged from 2 feet above normal on the western Louisiana coast and near Pensacola, Fla., up to 6 feet above normal along the southeastern Louisiana and Mississippi coasts. Flooding from heavy rains occurred through southeastern Louisiana and near the Mississippi and Alabama coasts.

Heavy rains with totals up to 11 inches fell on Oklahoma and eastern Texas, resulting in local flooding as a cold front moved through the area. Cyclonic conditions are apparent in that region on the mean map (fig. 3C).

A small tropical depression formed south of Louisiana on the 16th and entered northwestern Florida, causing

heavy precipitation in parts of the Southeast. It is possible that this depression was the beginning of hurricane Frieda, which developed off Bermuda on September 20 (fig. 6 and Chart X). Esther and Frieda will be discussed in greater detail in the following sections.

Warm and dry weather still prevailed over a narrow strip along the Pacific coast (fig. 4C and 5C), partly due to a diminished sea-breeze circulation as cold inland temperatures predominated. The remainder of the Nation was unseasonably cool (fig. 4C) as polar anticyclones continued to traverse the Great Plains (Chart IX). Departures from normal of the average temperature were -11° F. in Montana, -9° F. in Minnesota, North Dakota, South Dakota, and Wyoming, and -8° F. in Nevada. Record minimum temperatures and killing frost were experienced at stations in Oregon, Washington, Montana, and Idaho. The record minimum temperature in Helena, Mont., contrasted with record maxima there in both the first and fourth weeks of the month.

As a cold airmass moved slowly from the northwest and an upper-level Low from the southwest, significant snowfalls were recorded in the Rocky Mountain region with Helena, Mont., observing a record-breaking September accumulation of 13.4 inches and a 24-hour total of 9 inches. Drifts over 3 feet deep were reported in Logan Pass in Glacier National Park.

FOURTH WEEK

A major circulation change took place from the third to the fourth week as troughs and ridges moved rapidly eastward (fig. 3D). The mean trough in the United States sheared once more, with the southern portion becoming established along the coast of Lower California and the remainder marching eastward across the country to join the low-latitude trough of hurricane Frieda.

A trough remained in the Gulf of Mexico, extending northeastward into Tennessee, and was associated with heavy precipitation along the Gulf coast. The rains extended northward parallel to the trough in the southerly flow to its east. At the surface a weak wave developed in the northwestern Gulf on the 23d and stagnated until the 26th, when it began to drift slowly eastward (Chart X). A small area of heavy precipitation south of Hatteras during the fourth week was associated with a wave cyclone that moved northeastward parallel to that portion of the coast on the 29th–30th. The only other notable precipitation was in northern California and southern Oregon, where record 24-hour falls occurred as a consequence of the onshore flow and cyclonic conditions discussed in section 2. The rest of the country was dry as a large High became established in the Southwest (fig. 3D), and a long fetch of northwesterly flow invaded the northern two-thirds of the Nation.

The sharp reversal in the temperature field (fig. 4D) is easily understood against the background of the circulation changes. Cold weather was the rule in the eastern half of the United States. Temperatures dropped sharply as two thrusts of cold air were injected into the East, with anoma-

lies at Caribou, Maine, sliding from $+10^{\circ}$ F. for the third week to -8° F. Temperature departures from normal were as great as -11° F. at such diverse stations as Youngstown, Ohio, and Greenville, S. C. Record minima for the date, the month, and for so early in the season were set at many scattered stations throughout the East, Midwest, and South.

With clear skies and abundant sunshine in association with the High in the Southwest, the western half of the Nation experienced a heat wave of record-breaking proportions. Salt Lake City, Utah, broke maximum temperature records on the last 3 days of the month. New daily maxima were also set on those days and on the 27th at stations in Colorado, Montana, and Wyoming. The most extreme weekly temperature departures were $+12^{\circ}$ F. in Great Falls, Mont., and $+11^{\circ}$ F. in Salt Lake City.

Temperatures for the week were 5° F. below normal in a small pocket in the upper Sacramento Valley (fig. 4D). Early in the week, it was warm, but, from the 26th through the 30th, thick clouds blanketed the area and kept maximum temperatures suppressed an average of 16° F., while the minima remained near normal. On 3 days the percentage of possible sunshine ranged from 0 to 7 percent.

4. TROPICAL STORMS RELATED TO THE MONTHLY CIRCULATION

ATLANTIC STORMS

Of the four tropical storms which formed in the Atlantic and Gulf of Mexico during September two developed into hurricanes, compared to mean values of three storms and two hurricanes during the past 70 Septembers. Although four or more tropical cyclones have occurred slightly more than one-fourth of the time in September, since 1953 this frequency has been observed five times in succession. This can be explained in part perhaps by increased data.

Though conditions for tropical cyclogenesis were not the most ideal according to composite circulation types outlined by the author [1, 2] the circulation in September was more favorable than in the previous month. In August, westerly anomalous flow prevailed over a large part of the subtropical Atlantic, and, despite favorable sea-surface temperatures, only one storm formed. This storm developed in the Gulf of Mexico, which has been the preferred area this hurricane season. To date, five of the seven tropical storms (including two in September) have developed in the Gulf. 1936 was the only previous year on record in which five or more storms developed in the Gulf of Mexico. In that year a total of 17 tropical storms developed in the Atlantic region, so that even though 6 formed in the Gulf the concentration was not as great as this year. Conditions were favorable in the Gulf in September as easterly wave activity with concomitant cyclonic vorticity prevailed, and cooler than normal mid-tropospheric temperatures overlay warm sea-surface temperatures [8].

It is believed that the favorable climate for tropical storm formation includes warm sea-surface temperatures;

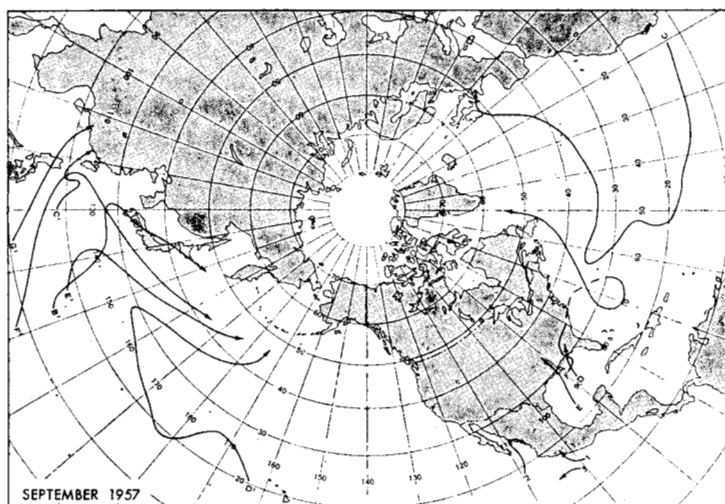


FIGURE 6.—Preliminary tropical storm tracks for September in both the Atlantic and Pacific Oceans. The track of Frieda (F) from the Gulf of Mexico to its "official" origin near Bermuda is hypothetical.

Palmén [11] set a criterion of 78° – 81° F. Since June 1957 all ship observations of water temperatures plotted on twice-daily synoptic charts have been tabulated for the 5° squares delineated in figure 7 (and for the squares extending east to Africa) and computed by 10-day and monthly means. The mean temperatures for the month of September appear in the center of each square (fig. 7). A comparison with the long-period (1887–1936) averages given by Riehl [12] is in the lower right corner, and the number of observations is given in the upper left corner of each box.

It is apparent that throughout September the sea surface was warmer than both the critical temperature of 81° F. and the long-period average in the ocean area shown. Temperatures were extremely high from June to September in the Gulf of Mexico, reaching a peak in August; and they exceeded or equalled the threshold value throughout the hurricane breeding ground of the Atlantic during both July and August, in addition to September. Despite this, tropical storm activity was suppressed during July and August. It is probable that a diminution in sea-surface temperature below a critical value would inhibit the formation of tropical storms, but that temperatures equal to, or in excess of, the threshold value do not guarantee formation unless synoptic conditions are also favorable.

This September the peak speed of the westerlies (jet), computed geostrophically from the monthly mean 700-mb. chart (fig. 1), was farther south than normal throughout the Atlantic (fig. 8A). Although it is popularly believed that when the jet is north of normal, tropical storm activity is great, and when south of normal diminished, this generalization is perhaps secondary in importance to the wind distribution to the north of the normal breeding grounds. Note the belt of stronger than normal westerlies at mid-latitudes of the Atlantic, surmounting another one

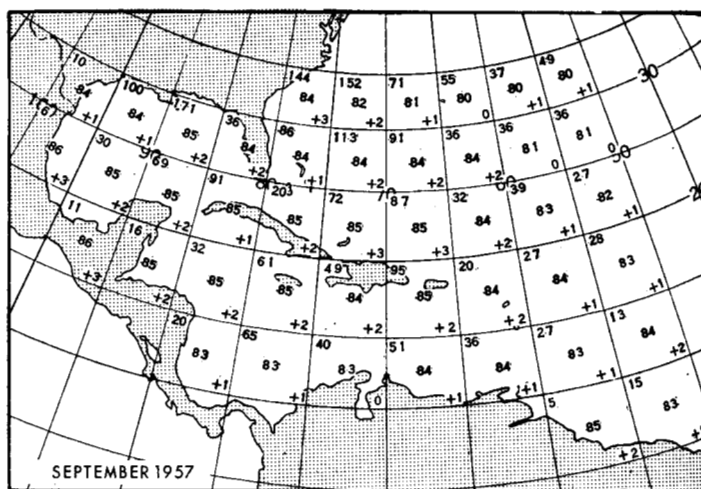


FIGURE 7.—Mean sea-surface temperatures ($^{\circ}$ F.) by 5° squares for the month of September 1957. Numbers in lower right hand corner of each box are the departure from normal in $^{\circ}$ F.; those in upper left give the number of ship observations (from twice-daily synoptic maps) on which the data are based. Water temperatures were especially warm throughout the area.

of easterly anomalous flow at lower latitudes (fig. 8B). This resulting increase in latitudinal wind shear encourages the fracture of extended troughs and the possible retrogression of their southern portions. Observation has shown the importance of a band of easterlies in the zone of formation [15], a condition realized this month as a continuous band of easterlies girdled lower latitudes from Africa to the western Pacific.

The behavior of the tropical storms (fig. 6) can be interpreted in terms of the monthly circulation (fig. 1). Both Debbie and Esther moved roughly parallel to the isopleths of 700-mb. height departure from normal. Namias [8] pointed out several cases of storm trajectories behaving in similar fashion. In addition, Esther moved northward just east of the mean trough for September, and Debbie moved northward just east of the mean trough for mid-August to mid-September (dashed trough in fig. 1). Such behavior has been noted in the case of Audrey by Klein [6], who lists many other *Monthly Weather Review* articles on the weather and circulation illustrating similar hurricane motion in relation to the mean circulation.

The recurvature of Carrie also paralleled a mean trough. This trough in the western Atlantic was not merely a reflection of the passage of the storm on 700-mb. heights in the region traversed, since removal of the days when Carrie was in that region from the 30-day mean does not completely eliminate the trough (not reproduced).

Carrie had an extremely long life, traveling approximately 6,000 miles in 24 days, and was classified as a hurricane for 20 days from the Cape Verde Islands to a point east of the Azores. The maintenance of the hurricane circulation for so long a period is associated with its oceanic trajectory and points up many problems involv-

ing atmospheric vortices. Carrie reached its greatest intensity about 1,000 miles east of Puerto Rico in the area where the monthly mean 700-mb. vorticity (computed from fig. 1, but not reproduced) was much more cyclonic than normal. (An indication of this vorticity is the -10 center in the height anomaly field of fig. 1.) At that time its winds were 160 m. p. h.; though hurricane-force winds did not affect any land areas, Carrie presented a hazard to North Atlantic shipping during its long existence. On September 21, Carrie was associated with the sinking of the German sailing vessel *Pamir* with a loss of 80 lives.

Hurricane Frieda reached its greatest intensity in an area of cyclonic vorticity near the apex of the mean trough traversed by Carrie. Its motion subsequent to its intensification does not fit the 30-day mean pattern as well as it does the 5-day patterns (section 5). However, features of the monthly mean that do appear to have influenced its path, and also that of Carrie, are the prevailing ridge along the east coast of the United States (fig. 1) and, particularly, the stronger than normal westerlies over the Northeast (fig. 8) which deterred tropical storm penetration into that area [9, 1].

EASTERN PACIFIC

Of interest this month were the three tropical storms which formed in the eastern Pacific near Mexico (fig. 6), one of which was a hurricane. They formed in an area of predominantly below normal heights on the mean 700-mb. chart, and two of them moved toward the north in the southerly flow ahead of the mean trough. The third storm had a forward speed of about 10 m. p. h. A final bulletin issued by San Francisco on the 27th stated that it was impossible to follow that storm beyond 15° N., 104° W., due to lack of reports in the area. Subsequently a circulation was detected at 0000 GMT on October 1 at 19° N., 119° W. (not shown on fig. 6). During October the storm developed into a hurricane that recurved northeastward across Lower California into Mexico. If storm number 3 (fig. 6), which could not be tracked beyond the position given above, had continued to drift west-northwestward with a speed of 11 m. p. h., it would have arrived at the point where the circulation was detected on October 1. It is therefore conceivable that these two storms were the same one.

WESTERN PACIFIC

When this month began, Typhoon Bess (B' on fig. 6) had already formed. Five other typhoons were observed in the western Pacific during September, although only four typhoons formed. This paradox is the result of semantics, since tropical storms with winds in excess of 75 m. p. h. are called hurricanes east of 180° and typhoons west of 180° , and a hurricane observed first on September 4 at 163° W. was renamed typhoon Della (D') after it crossed the 180th meridian on the 7th.

Four of the six typhoons observed this month recurved in the southerly flow between the Asiatic trough and the subtropical High. These four storms recurved sharply

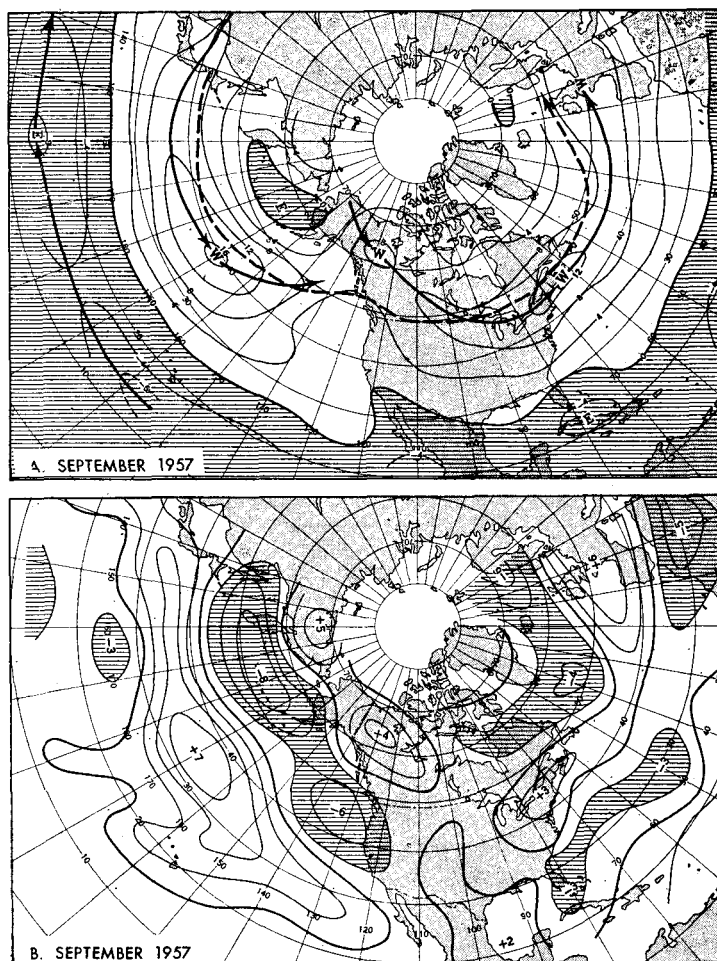


FIGURE 8.—Mean 700-mb. isotachs of the zonal wind speed component (A) and its departure from normal (B) (both in meters per second). Solid arrows in (A) indicate positions of the mean axes of 700-mb. zonal wind maxima, and dashed arrows give their normal September position. Centers of easterly and westerly flow are labeled E and W, respectively. Easterly flow is considered negative and shaded. The hatched shading in (B) delineates areas where the departure from the normal zonal flow equalled or exceeded 2 meters per second from the east. Note the effect of blocking in middle and high latitudes, producing anomalous flow components from the east.

into the Aleutian Low south of a strong blocking High over Kamchatka. This Low was regenerated from time to time and acted as a sink for the cyclonic vorticity of these typhoons and a source for the cyclone tracks leaving that area (Chart X) and traveling across the top of the blocking ridge in the eastern Pacific.

5. TROPICAL STORMS RELATED TO THE 5-DAY MEAN CIRCULATIONS

The relation of the tropical storms of the Atlantic to the 5-day mean circulations deserves special attention. Features that were not too clear in the previous section will be brought into sharper focus. Each 5-day mean map (fig. 3) will be discussed in chronological order with

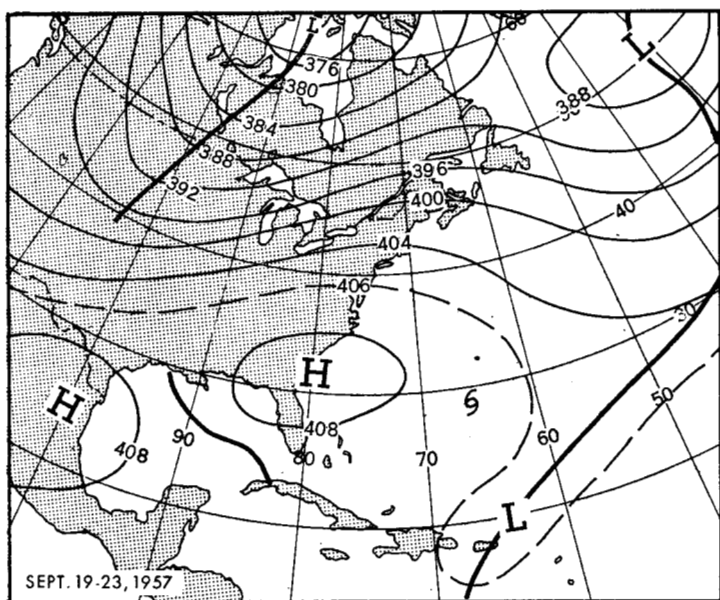


FIGURE 9.—Five-day mean 200-mb. contours (in hundreds of feet) for September 19-23, 1957, the period in which Frieda was detected. Although the position of Frieda on September 21 (designated by the tropical storm symbol) appeared favorable for deepening, it did not deepen until the 25th when a westerly trough moved into the area.

respect to its relation to the tropical storm(s) of that period.

Namias and Dunn [10] hypothesized that the frequency of tropical storms of the Cape Verde type depends on the degree of development of the Azores ridge to the north. They stated that when the ridge of the Azores upper-level anticyclone is thrust strongly northeastward into Europe, cyclonic vorticity is injected into a trough off the African coast. They cited the antecedent conditions associated with hurricane Connie in August 1955 as an example of this type of development (their fig. 4). The author [16] has noted that conditions favorable for tropical storm generation in the Cape Verde area are such that large positive height anomalies appear near western Europe—possibly a manifestation of a stronger than normal Azores High extending far northward. The 700-mb. conditions prior to the formation of Carrie on September 2 (not reproduced) were very reminiscent of those preceding Connie, and provide further evidence for the hypothesis expounded by Namias and Dunn [10].

On the morning of September 7, a weak cyclonic circulation, Debbie, developed in the central Gulf of Mexico as the result of juxtaposition of an easterly wave and a stagnant trough aloft. Debbie intensified very little as it moved northeastward in the southerly flow ahead of the trough. Conditions were not favorable for intense deepening as southwesterlies were above the storm in both the middle and upper troposphere [13]. On September 8 (fig. 3a) Debbie went inland at Fort Walton, Fla., with winds of 40 m.p.h. (associated weather described in section 3).

Subsequent to its development on September 2, Carrie moved eastward south of a zonally oriented ridge (fig. 3A). The storm continued its westward march until the 10th when it encountered a low-latitude trough (fig. 3a) that had moved about 5° to the east from its former position (fig. 3A) and influenced Carrie's abortive recurvature. This low-latitude trough joined with a high-latitude trough that deepened as the upstream wave train amplified. Carrie drifted north in the mean trough at about 5-10 m. p. h. during the period September 10-14 (fig. 3B).

The strong ridge along the east coast of North America (fig. 3B) sheared during the next period (fig. 3b), and the westerlies over eastern Canada increased greatly in speed. As a result, the short wavelength between the mid-continental trough and the western Atlantic trough (fig. 3B) could no longer be supported, and the upper portion of the Atlantic trough sheared and amalgamated with a retrogressive trough in the eastern Atlantic. In association with these fundamental changes in the circulation, a ridge crested across the Atlantic to the north of Carrie, impeding its northward motion. Carrie turned to the northwest on the 15th and on the 17th recurved sharply as it came under the influence of the westerlies north of the ridge.

A mid-tropospheric cyclonic circulation over Nicaragua on September 12 drifted northwestward to the southwestern Gulf of Mexico on the 15th. Tropical storm Esther formed under this circulation at the base of the mid-continental trough. Relatively few of the Gulf storms deepen into hurricanes (less than one-third of the September storms), and Esther was part of the majority. As it moved northward just to the east of the trough, the base of the westerlies was apparently too low for major deepening [14]. Esther moved inland on the southeastern Louisiana coast about daybreak of the 18th and continued northward up the Mississippi Valley, losing its identity on the 19th (fig. 3C).

On the 16th a weak tropical depression was located in the northeastern Gulf of Mexico, and it moved inland that morning (fig. 3b). This Low moved northeastward and eastward to the North Carolina-South Carolina border early on the morning of the 18th. At that time it was a frontal wave which progressed eastward by a method of discontinuous cyclogenesis. It is thought that this wave cyclone eventually deepened into hurricane Frieda.

Dunn [3] has indicated that trailing, stationary, or fractured portions of old polar troughs may provide the initial concentration of cyclonic vorticity necessary for hurricane formation, a common occurrence in the area between the Bahamas and Bermuda [16]. It was mentioned in section 4 that Frieda formed at the apex of the monthly trough associated with Carrie; but these two storms can be even more closely linked. As Carrie moved rapidly eastward (Sept. 17 to 25) it left a trough behind. The extratropical Low over the South Atlantic States deepened as it approached this concentration of cyclonic vorticity near Bermuda, and the "official" preliminary track places the origin of Frieda in that

vicinity (fig. 3c). It continued to move southward, steered by the large-scale flow which appears on the 5-day mean (also paralleling the isopleths of height anomaly) (fig. 3c). Such a path, while uncommon, is not unprecedented; e. g., the famous "Yankee" hurricane of 1935 and a tropical storm in October 1938.

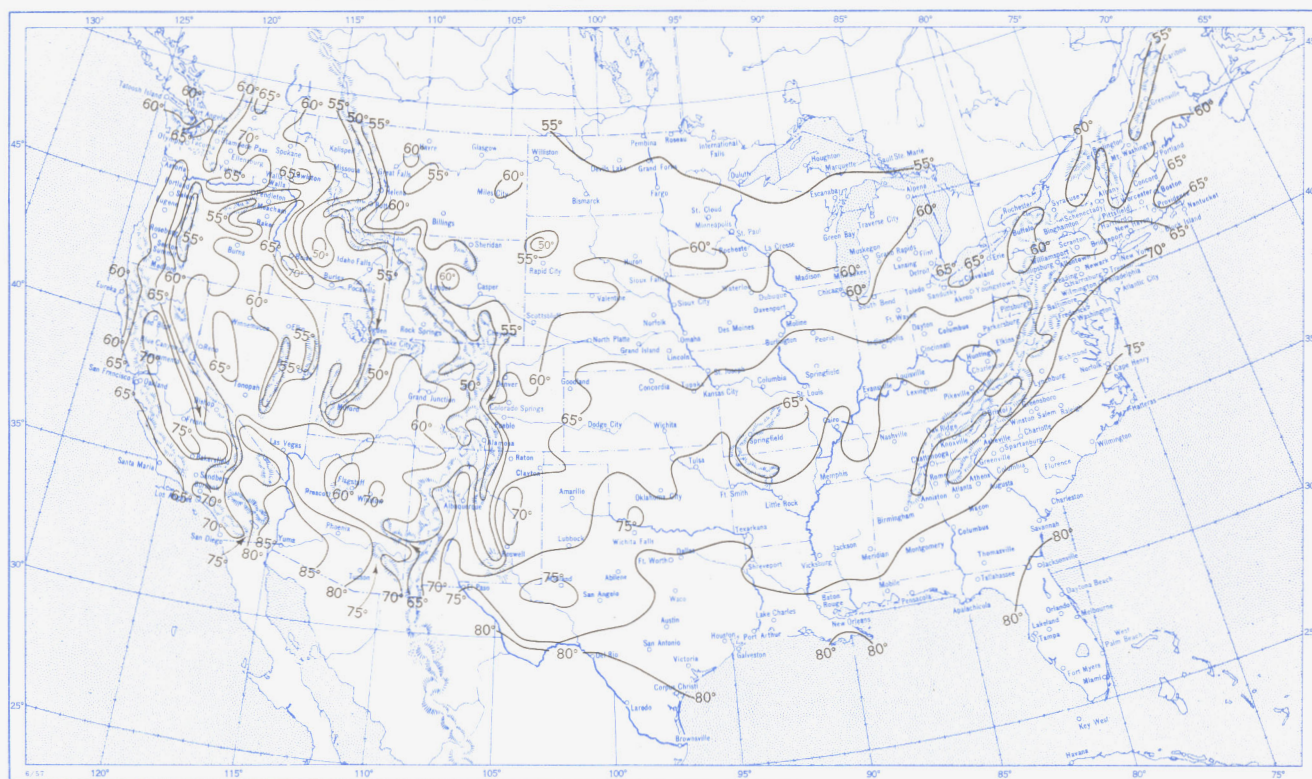
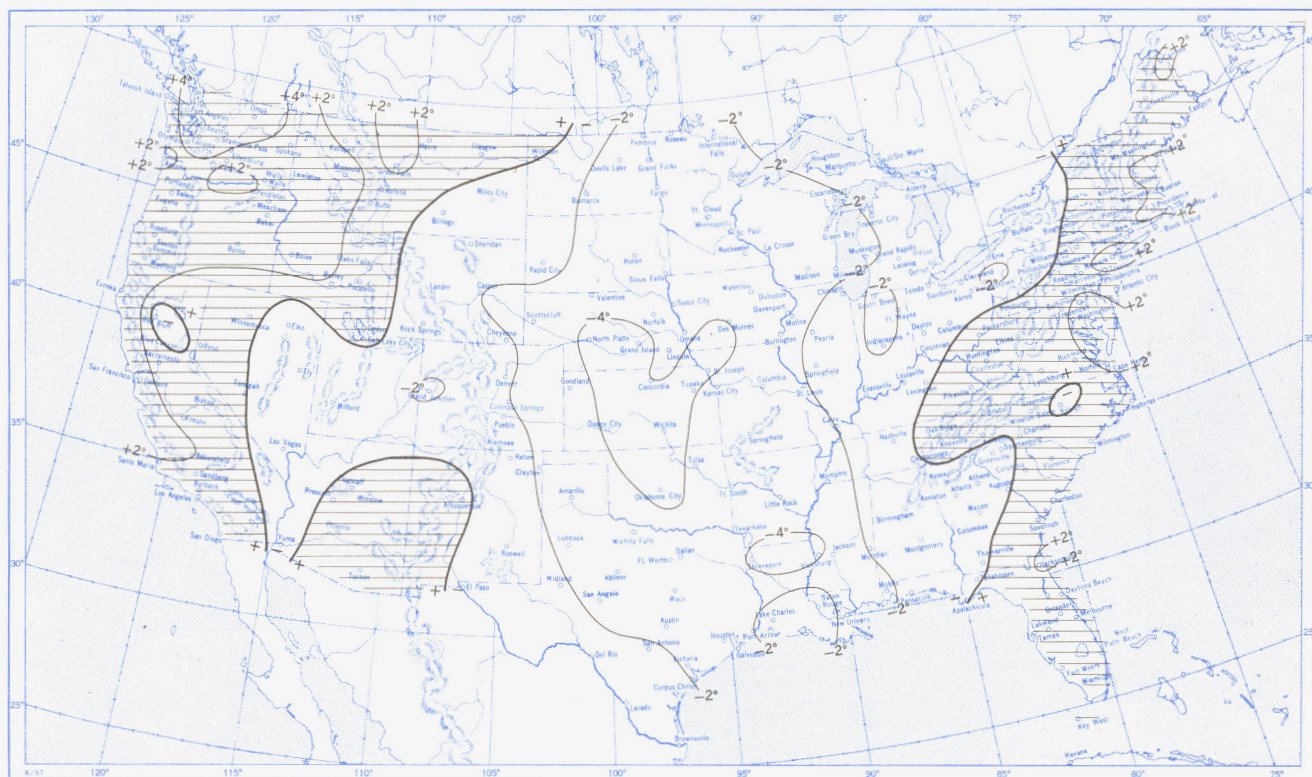
As Frieda continued to move southward and then loop northward (fig. 3, C and c), it proved to be an exception to the rule [13] that a northerly current at 200 mb. is favorable to deepening (fig. 9). This exception was especially noteworthy in view of the fact that the anticyclone above Frieda was part of a ridge of the long-wave pattern in the westerlies during a period of considerable amplitude.

During the period September 21–25 (fig. 3c) large-scale retrogression ceased and eastward motion again became established. This eastward motion continued at an accelerated pace, and a deepened trough off the east coast of North America swept Frieda rapidly northward. It was not until this trough at both 700 mb. and 200 mb. came over the surface cyclone that the storm deepened to hurricane intensity (fig. 3D). It appears as if the intensification of Frieda cannot be divorced from the baroclinic conditions that accompany the transformation of tropical cyclones into extratropical ones. Trough intensification not only affects the motions of these storms but also provides a mechanism for extratropical development.

Meanwhile (fig. 3c) Carrie streaked eastward under westerly mean 700-mb. flow. On the 21st the *Pamir* sank in the vicinity of the storm, and on the 25th Carrie passed over Ireland as strong gales lashed the coast. It helped to deepen the Low over northern Europe on the last map of this series (fig. 3D).

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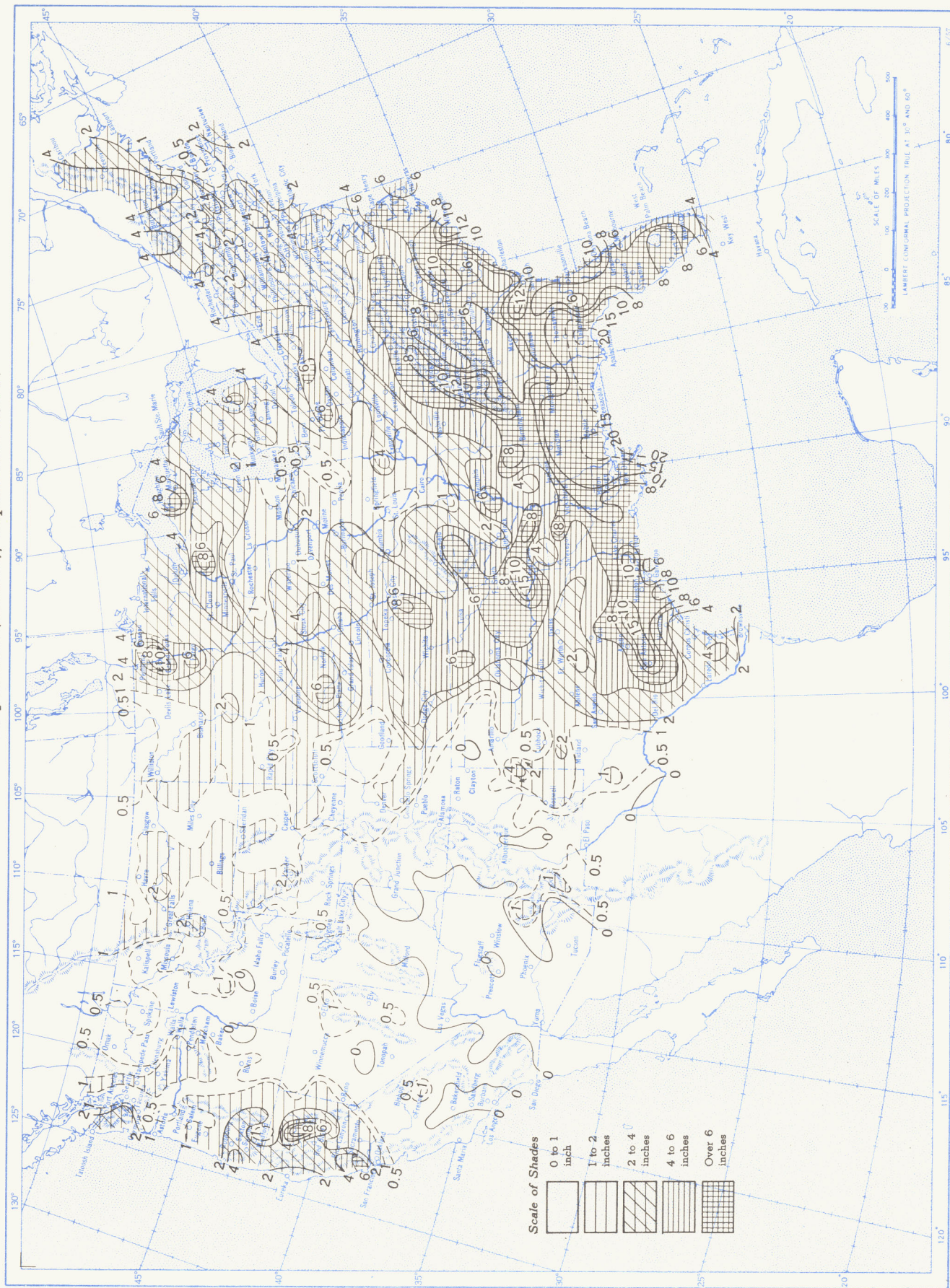
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Chart I. A. Average Temperature ($^{\circ}$ F.) at Surface, September 1957.B. Departure of Average Temperature from Normal ($^{\circ}$ F.), September 1957.

A. Based on reports from over 900 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.

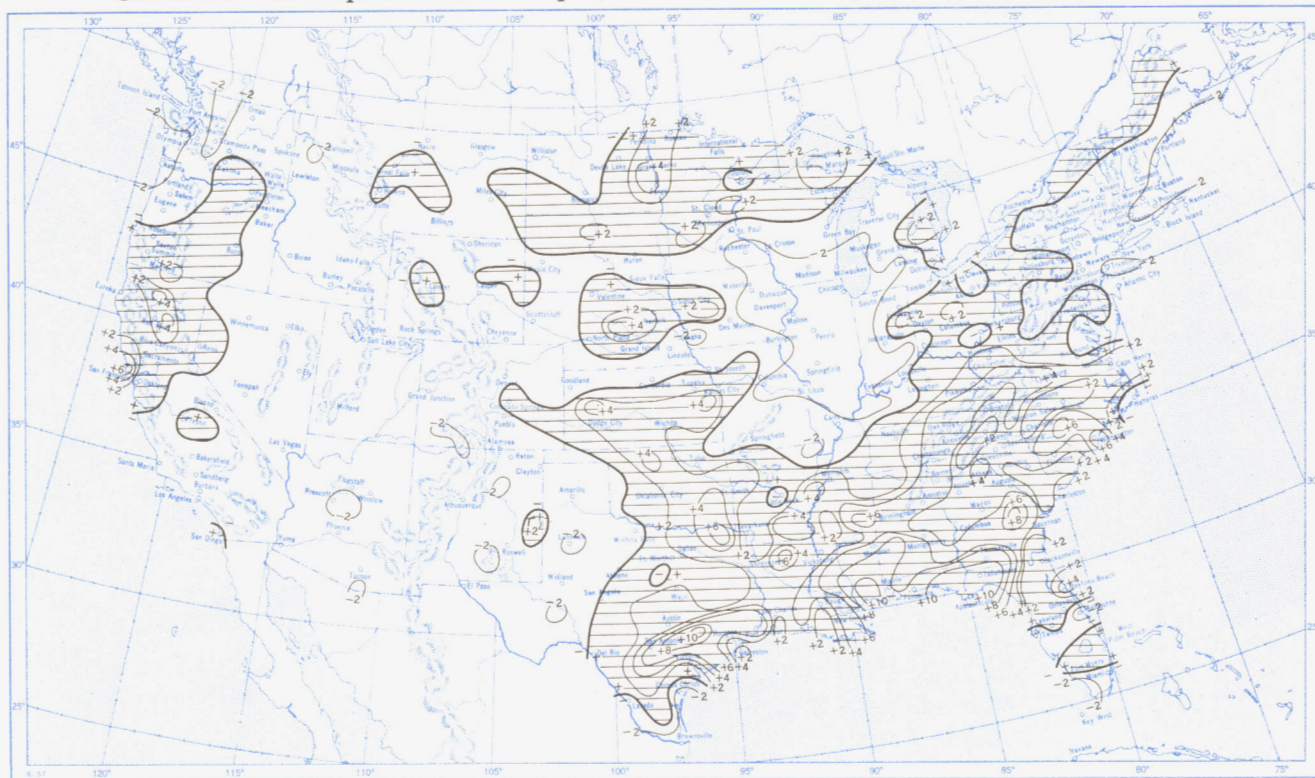
B. Departures from normal are based on the 30-yr. normals (1921-50) for Weather Bureau stations and on means of 25 years or more (mostly 1931-55) for cooperative stations.

Chart II. Total Precipitation (Inches), September 1957.

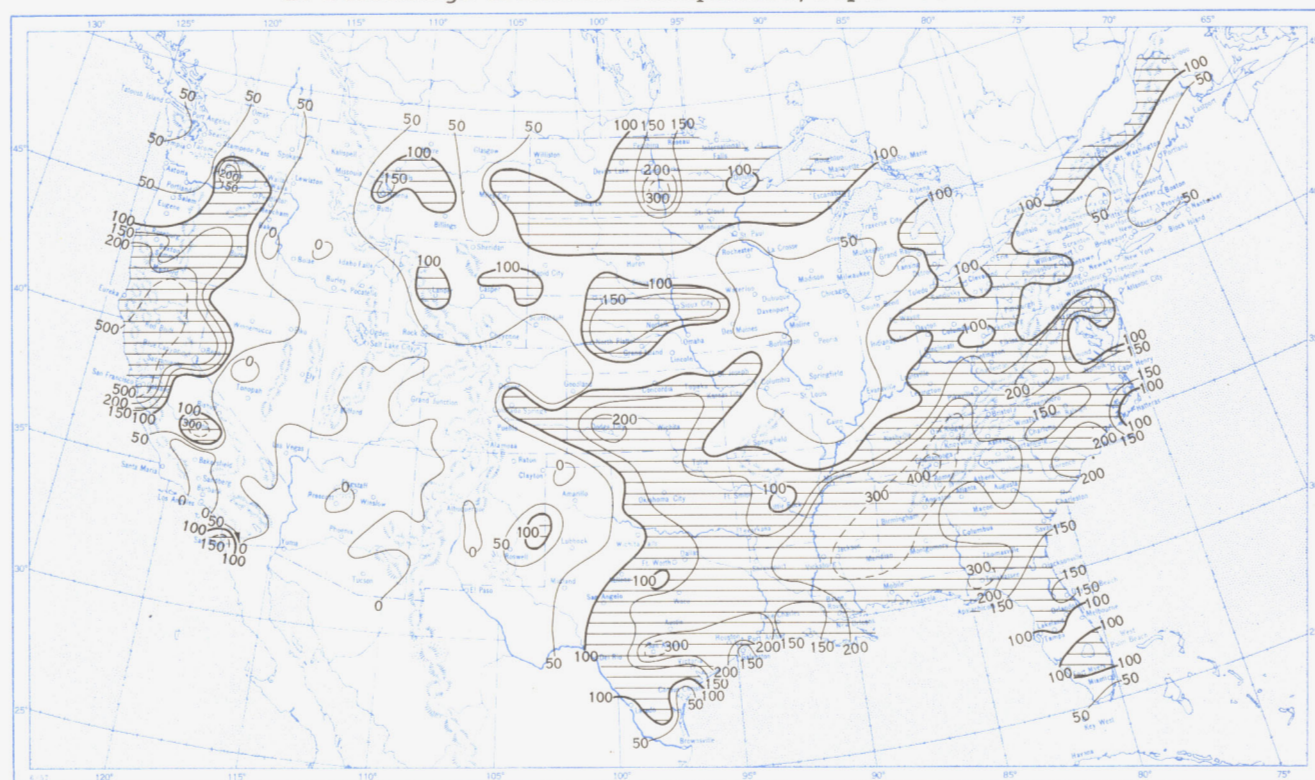


Based on daily precipitation records at about 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), September 1957.

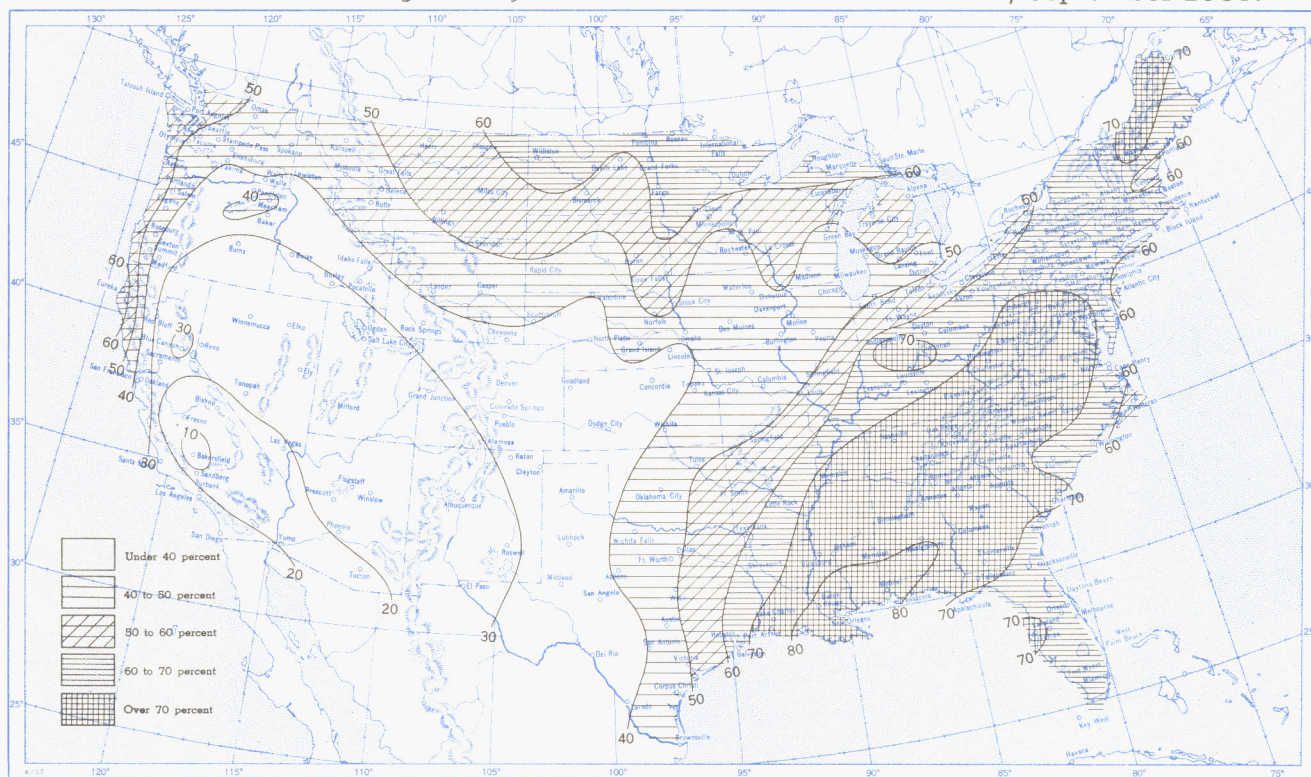


B. Percentage of Normal Precipitation, September 1957.

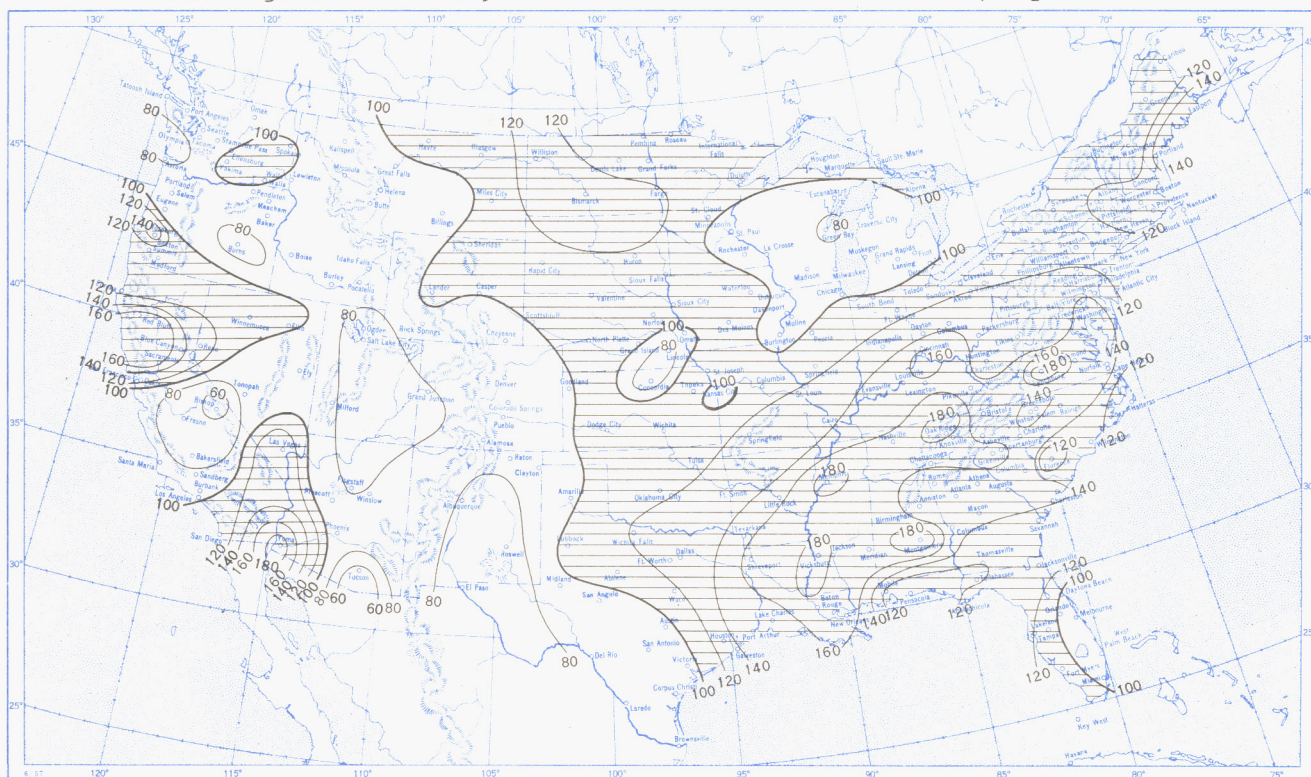


Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, September 1957.

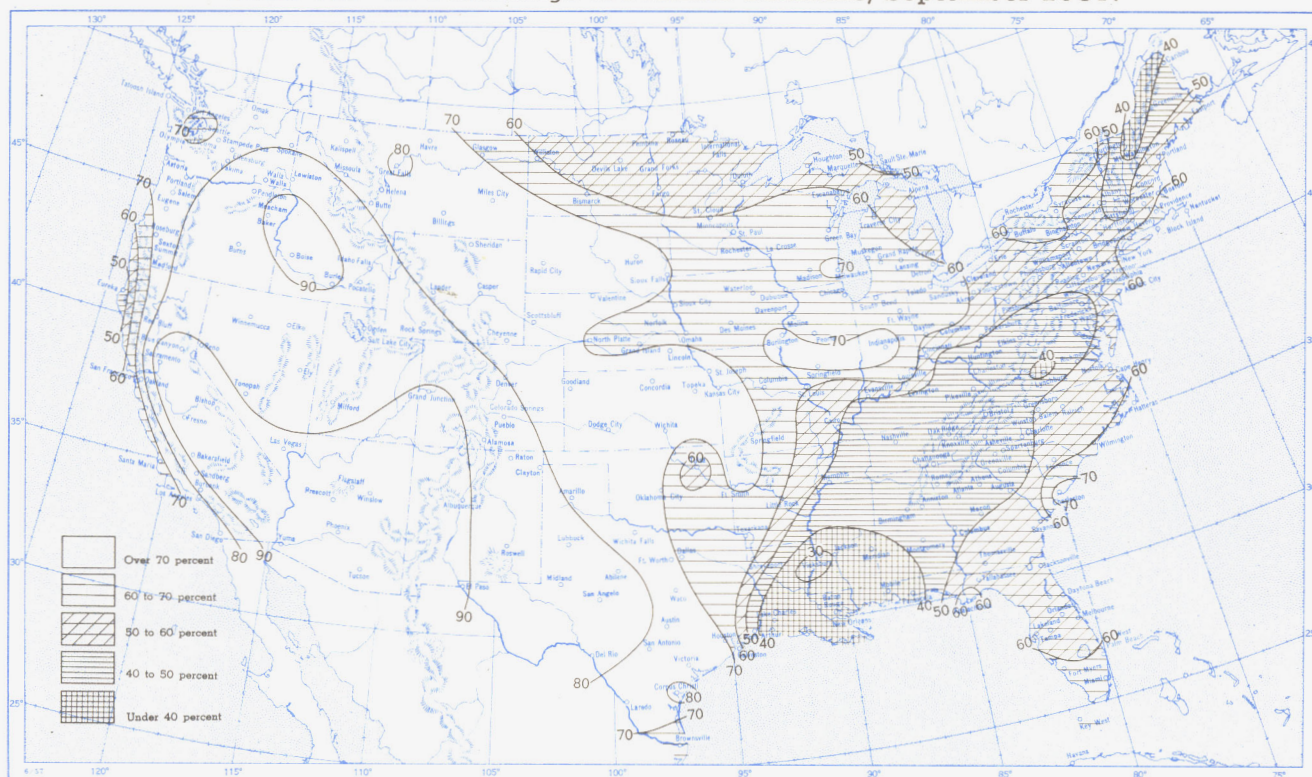


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, September 1957.

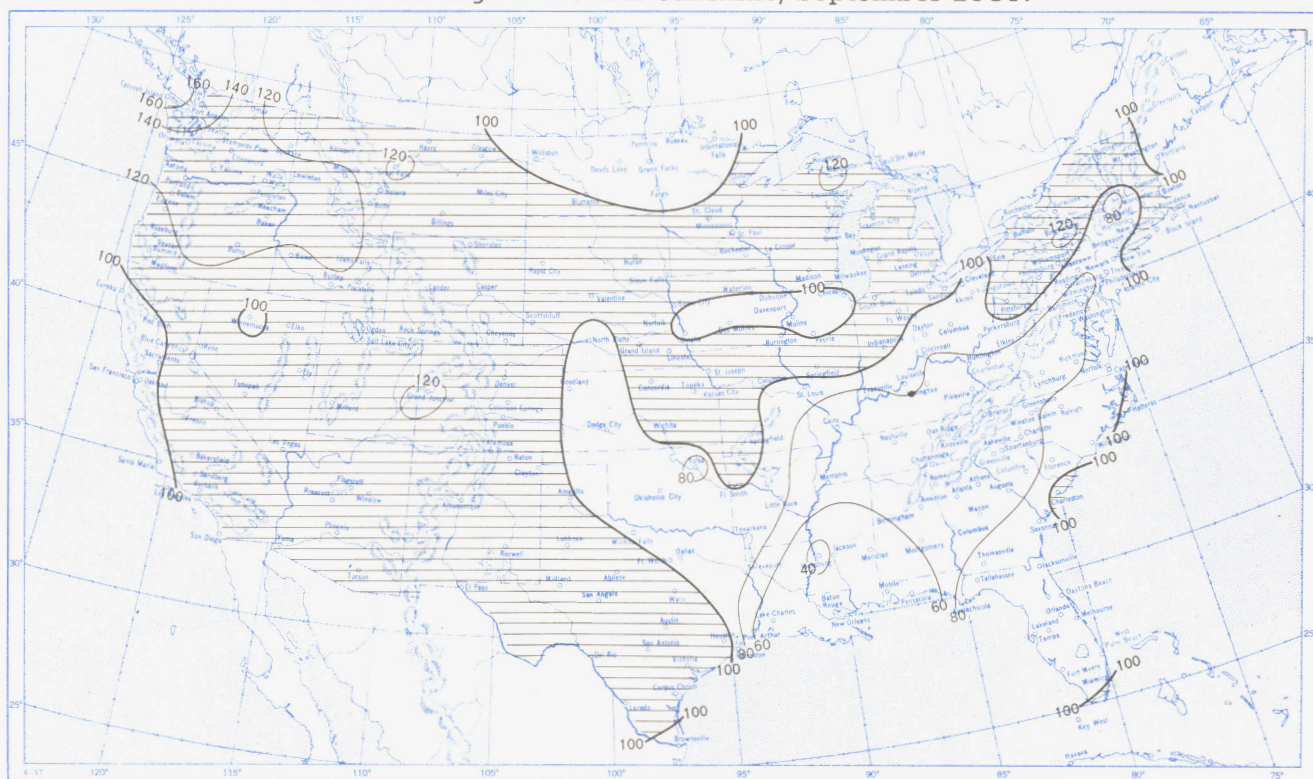


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, September 1957.



B. Percentage of Normal Sunshine, September 1957.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, September 1957. Inset: Percentage of Mean Daily Solar Radiation, September 1957. (Mean based on period 1951-55.)

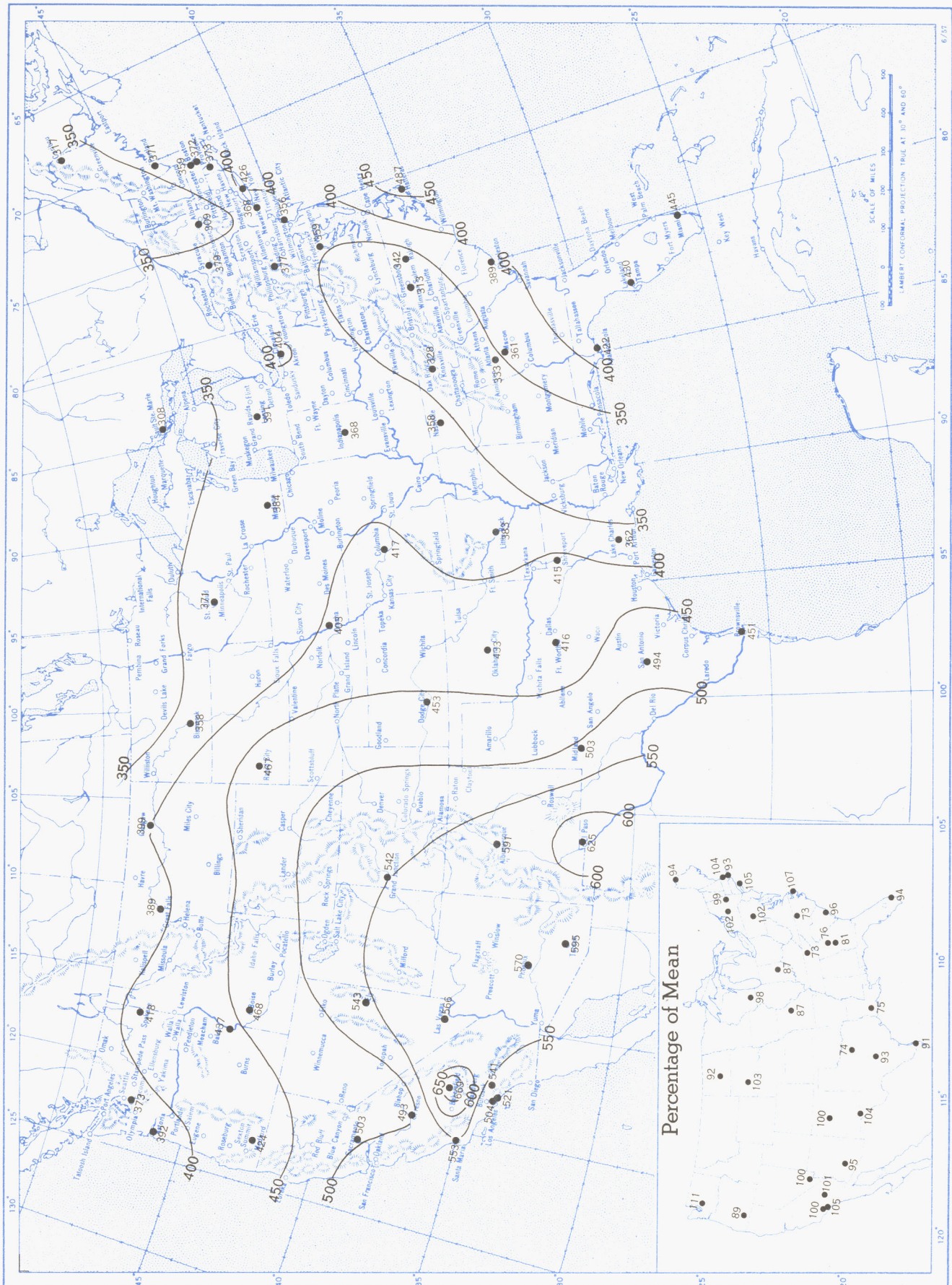
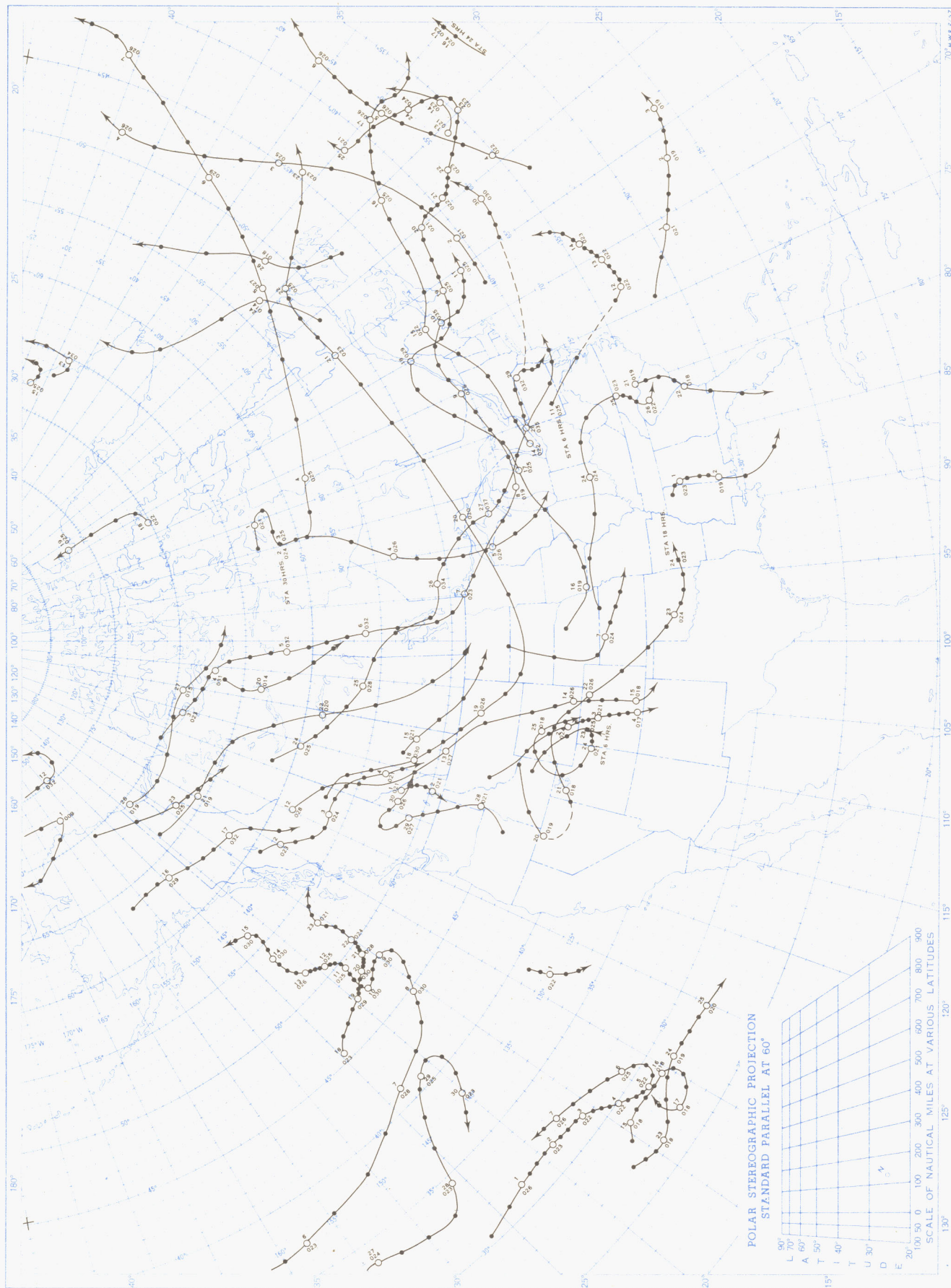


Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langley's (1 langley = 1 gm. cal. cm. ⁻²). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. The inset shows the percentage of the mean based on the period 1951-55.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, September 1957.



Circle indicates position of center at 7:00 a. m. E. S. T. Figure below circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, September 1957.

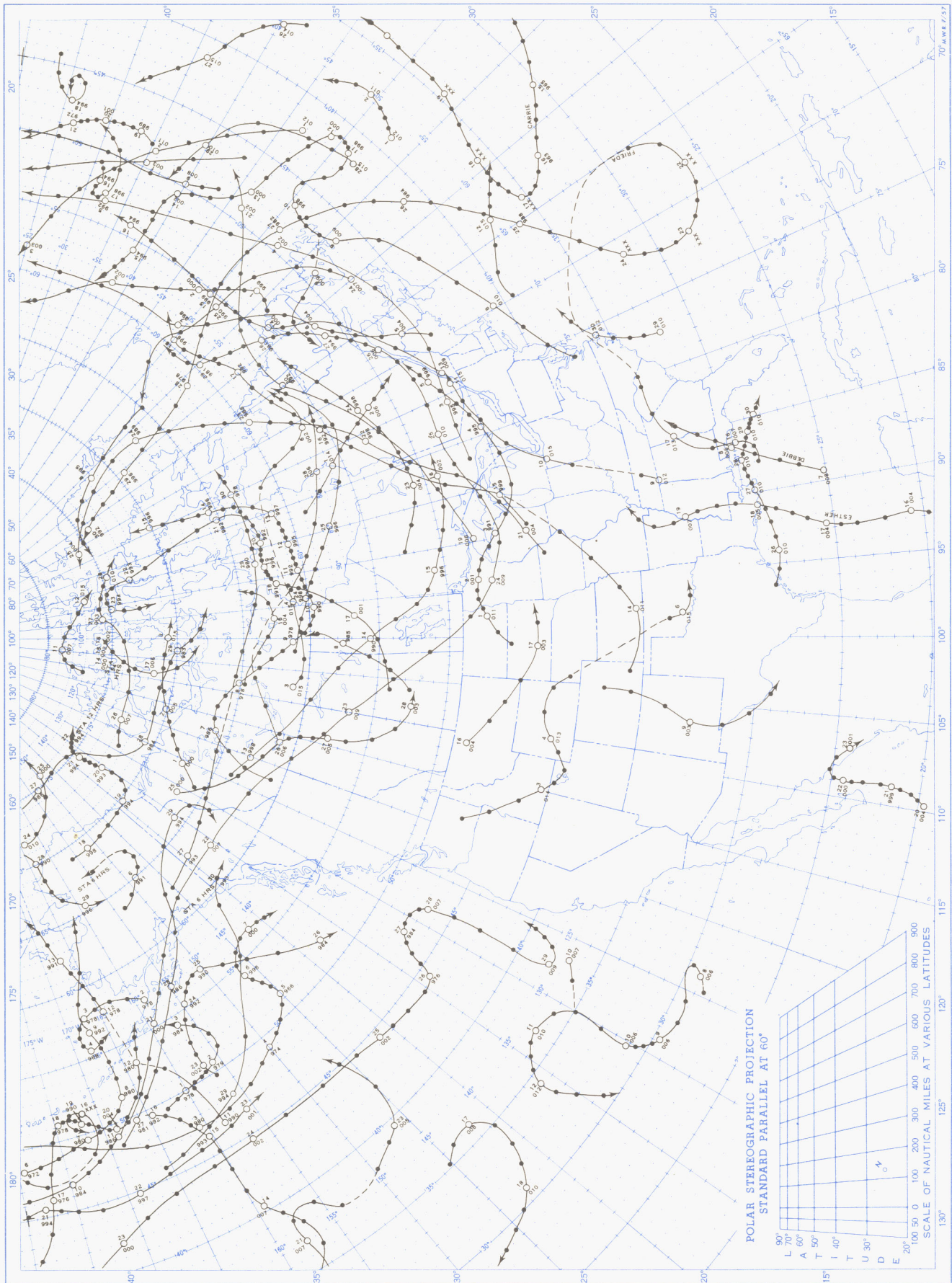
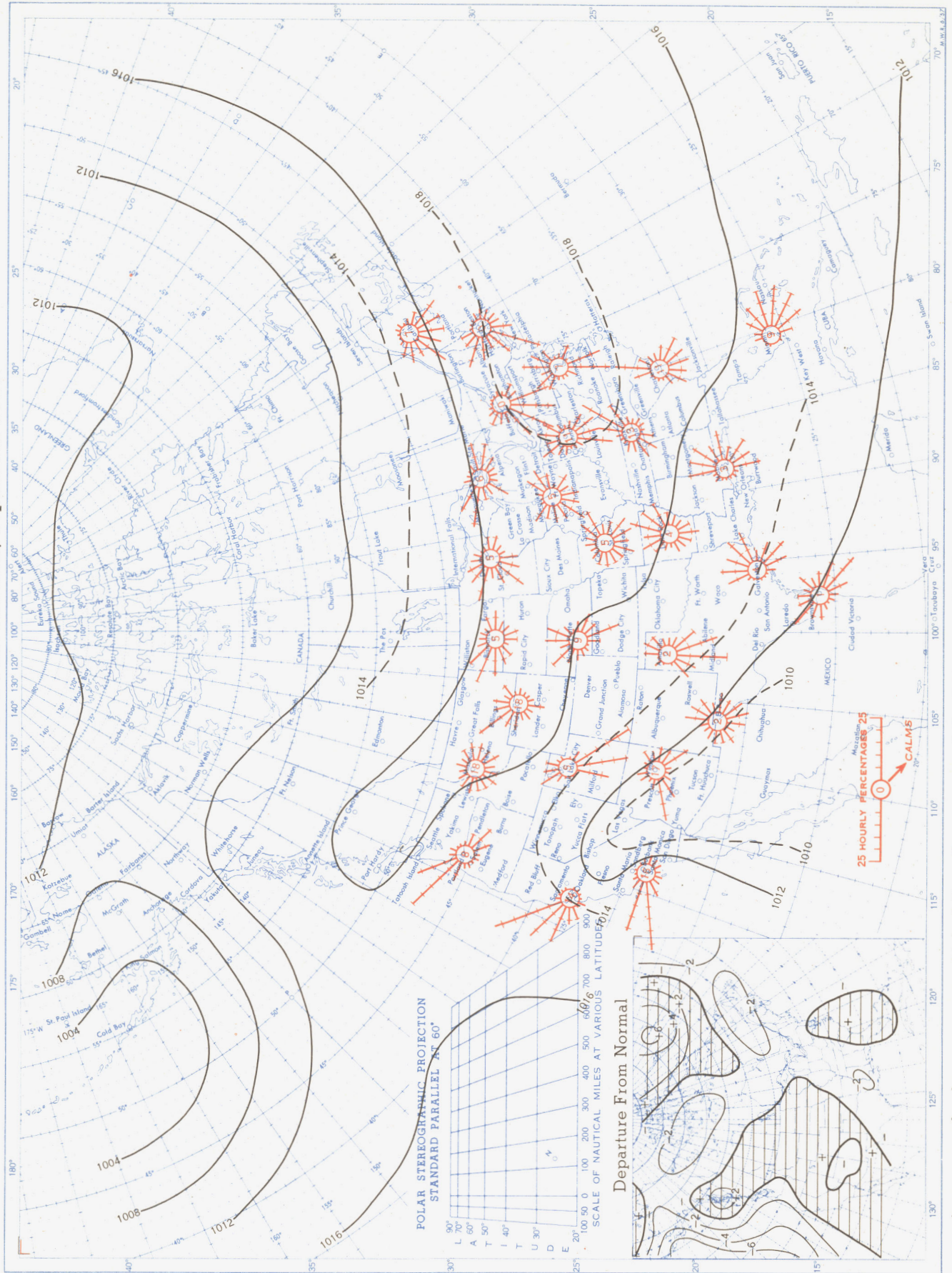


Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, September 1957. Inset: Departure of Average Pressure (mb.) from Normal, September 1957.



Average sea level pressures are obtained from the averages of the 7:00 a. m. and 7:00 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° inter-sections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. 850-mb. Surface, 1200 GMT, September 1957. Average Height and Temperature, and Resultant Winds.

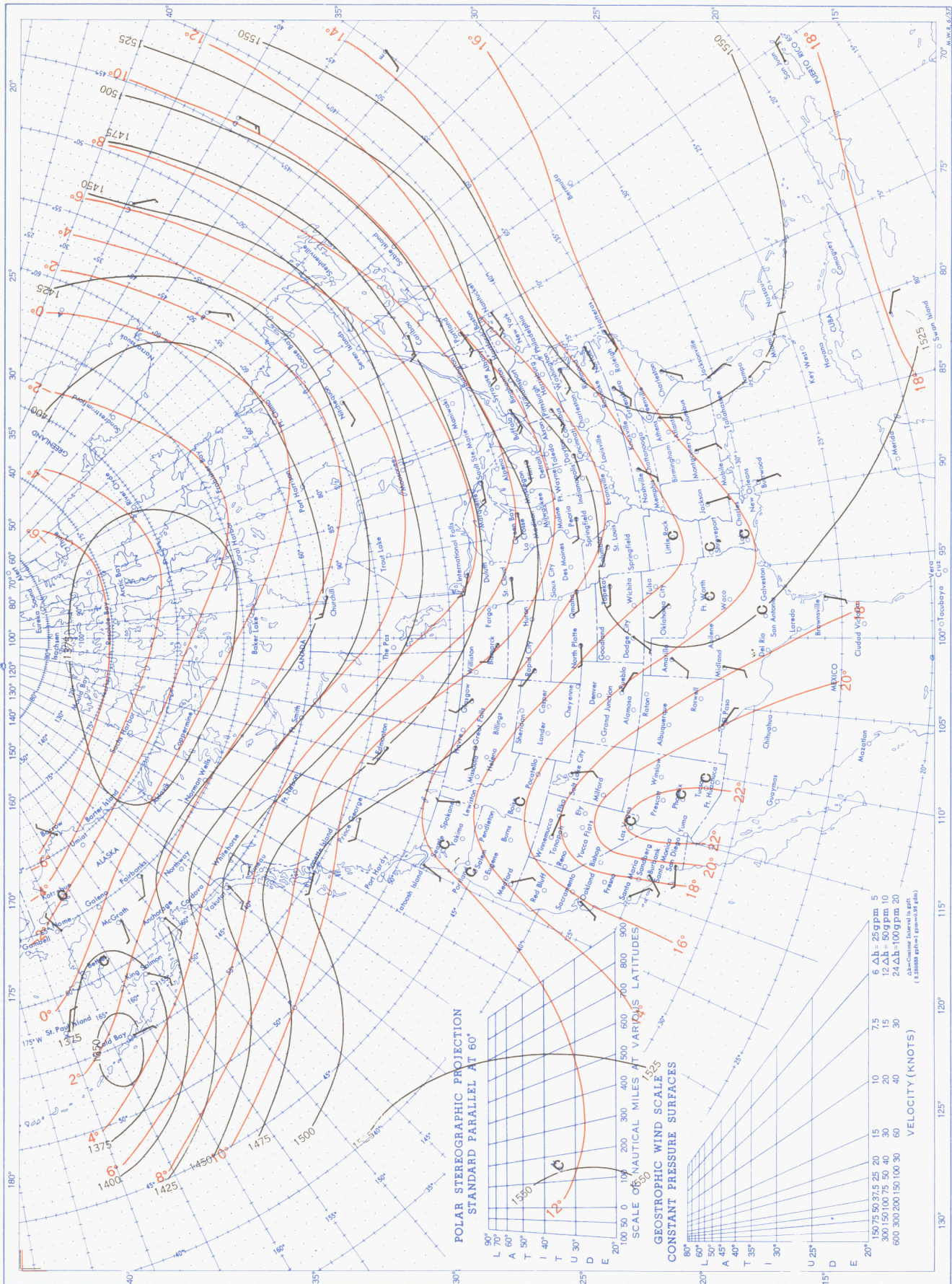
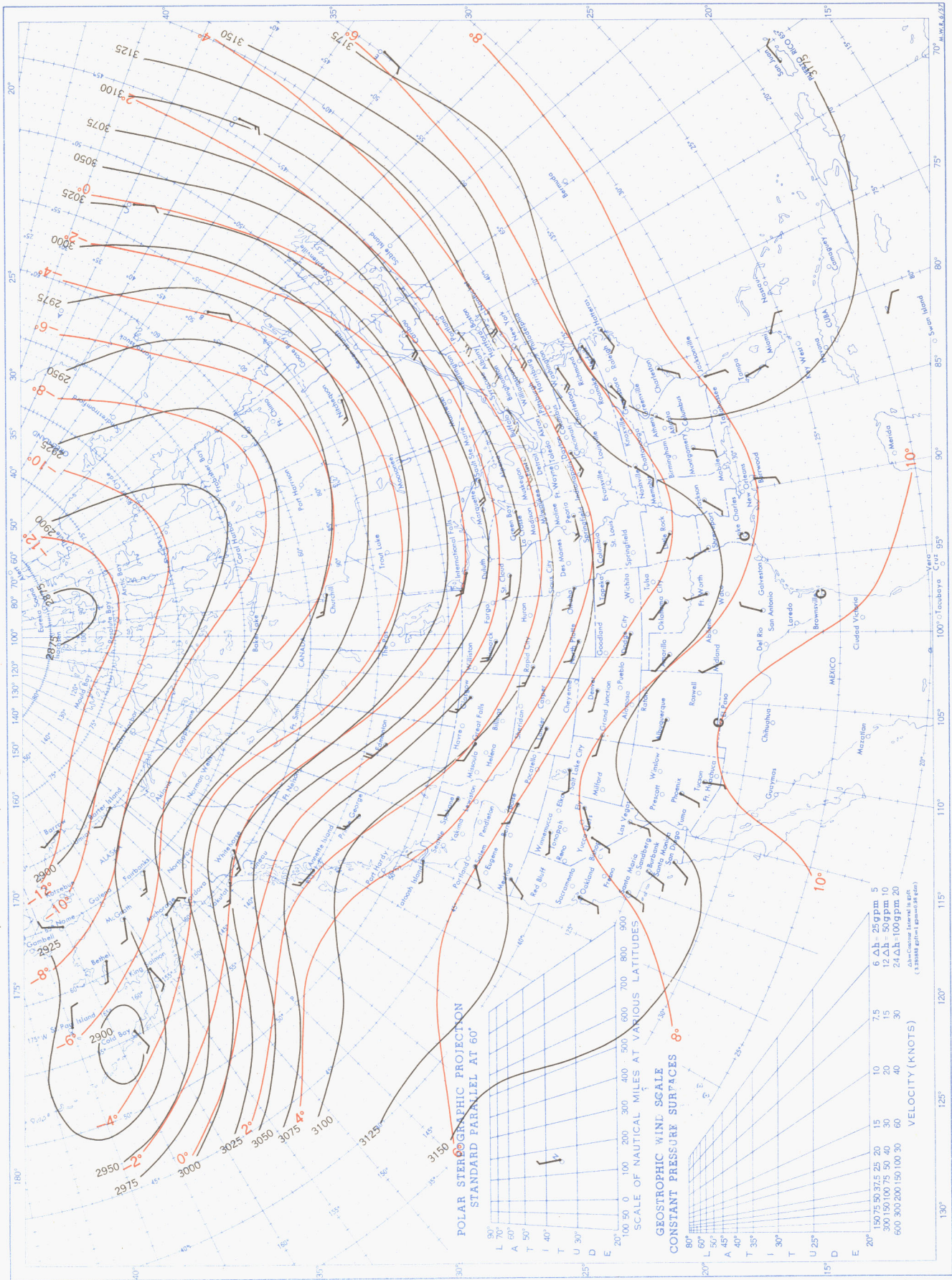
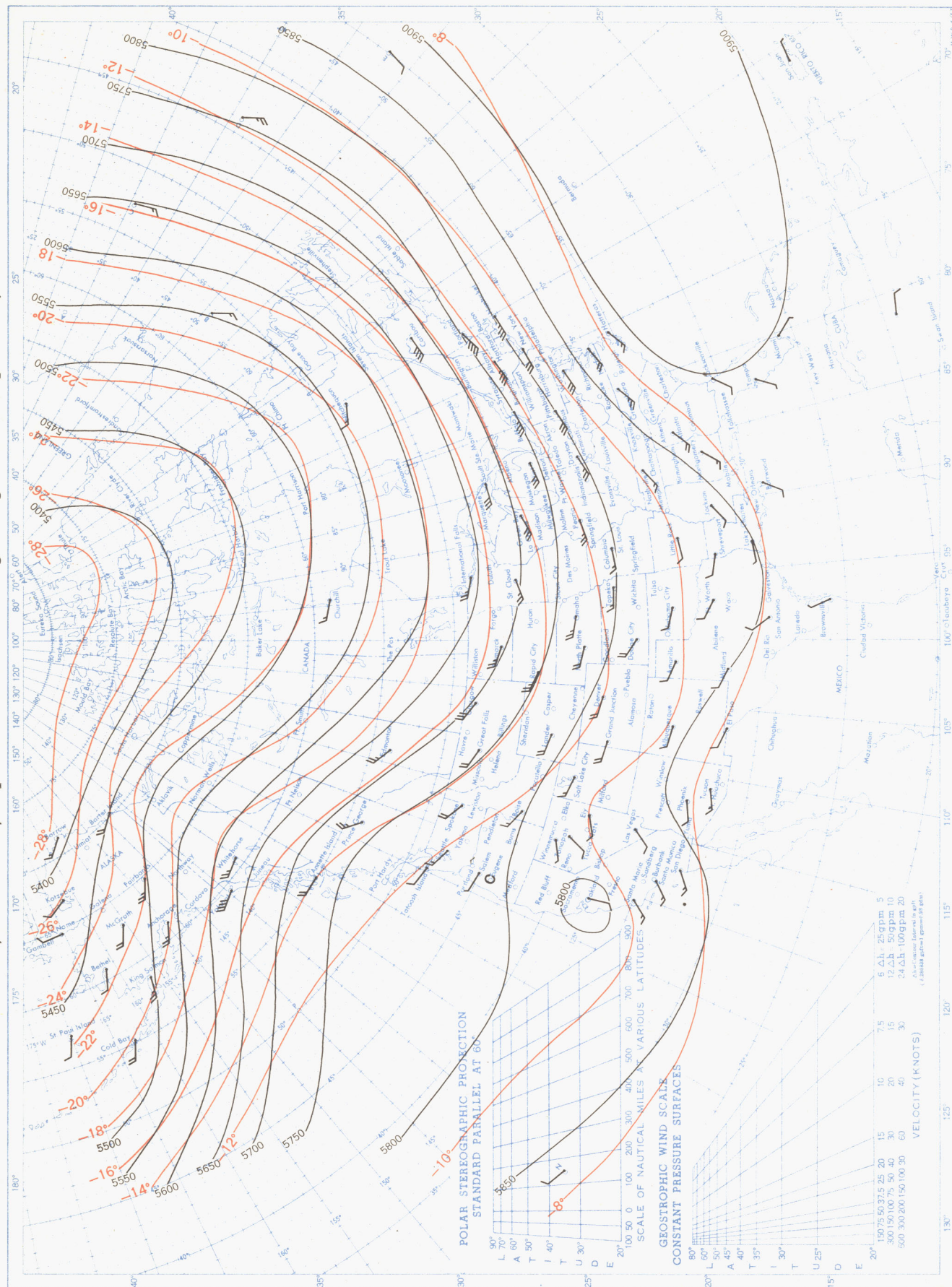


Chart XIII. 700-mb. Surface, 1200 GMT, September 1957. Average Height and Temperature, and Resultant Winds.



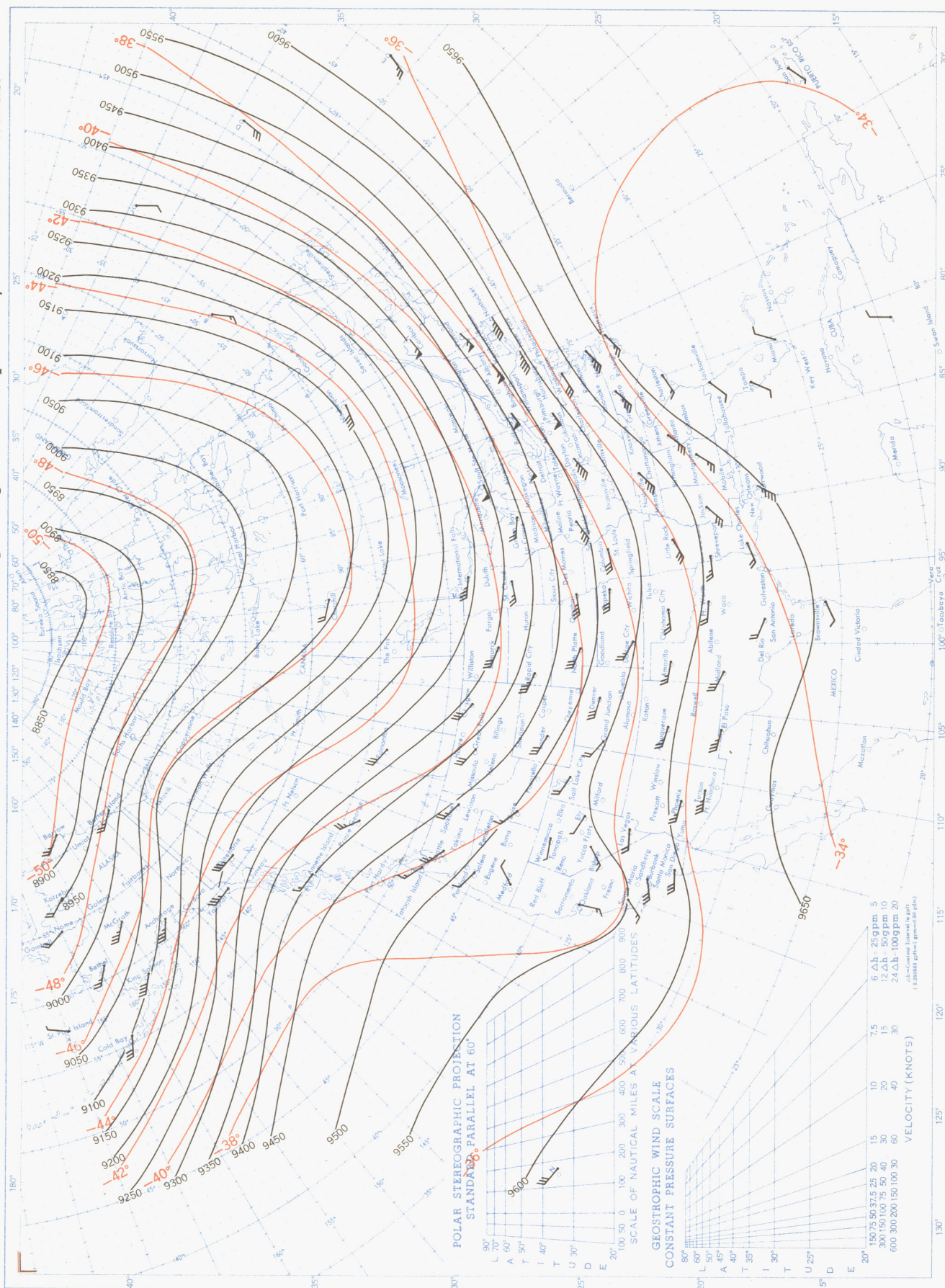
See Chart XII for explanation of map.

Chart XIV. 500-mb. Surface, 1200 GMT, September 1957. Average Height and Temperature, and Resultant Winds.



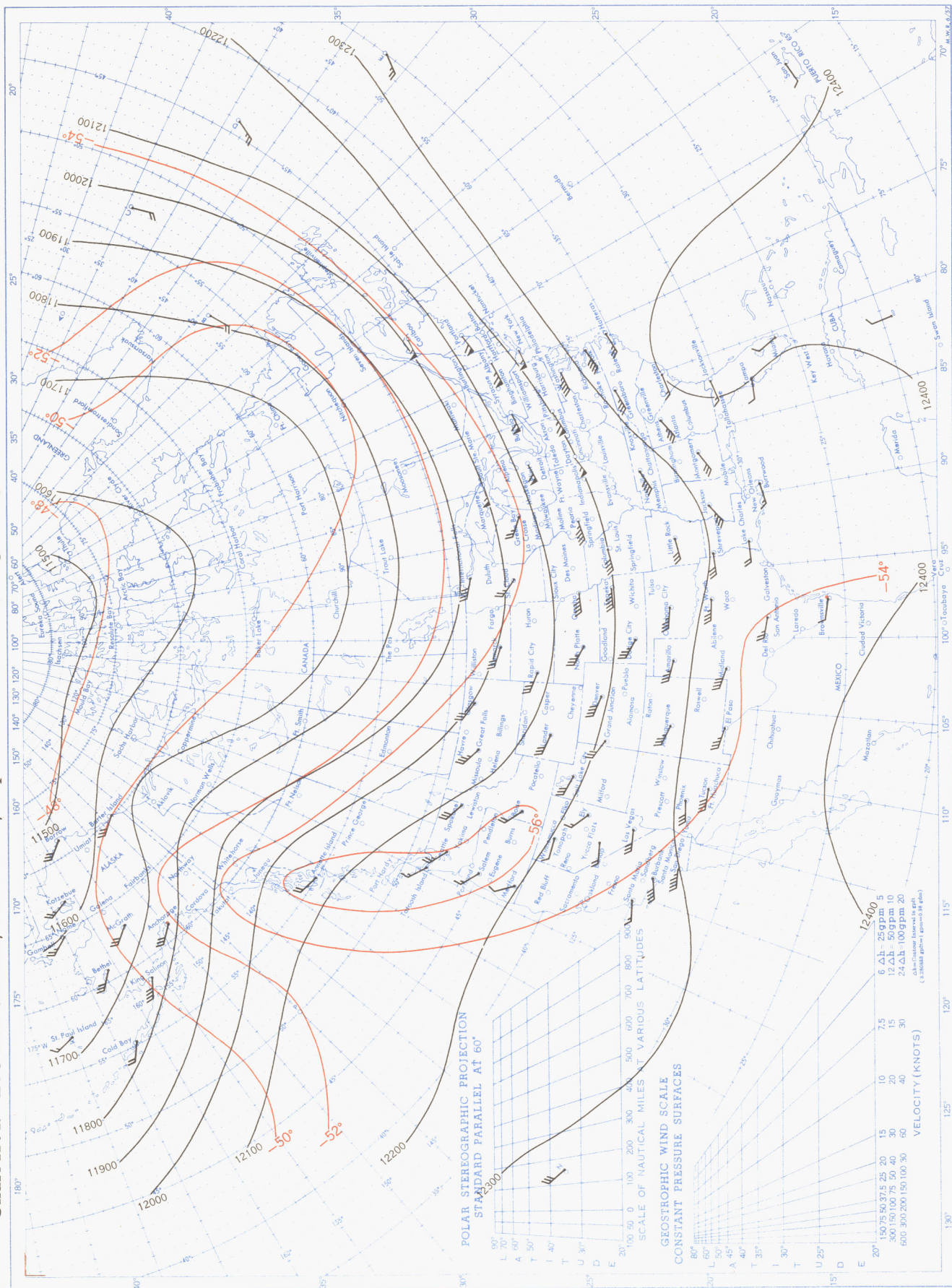
See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 1200 GMT, September 1957. Average Height and Temperature, and Resultant Winds.



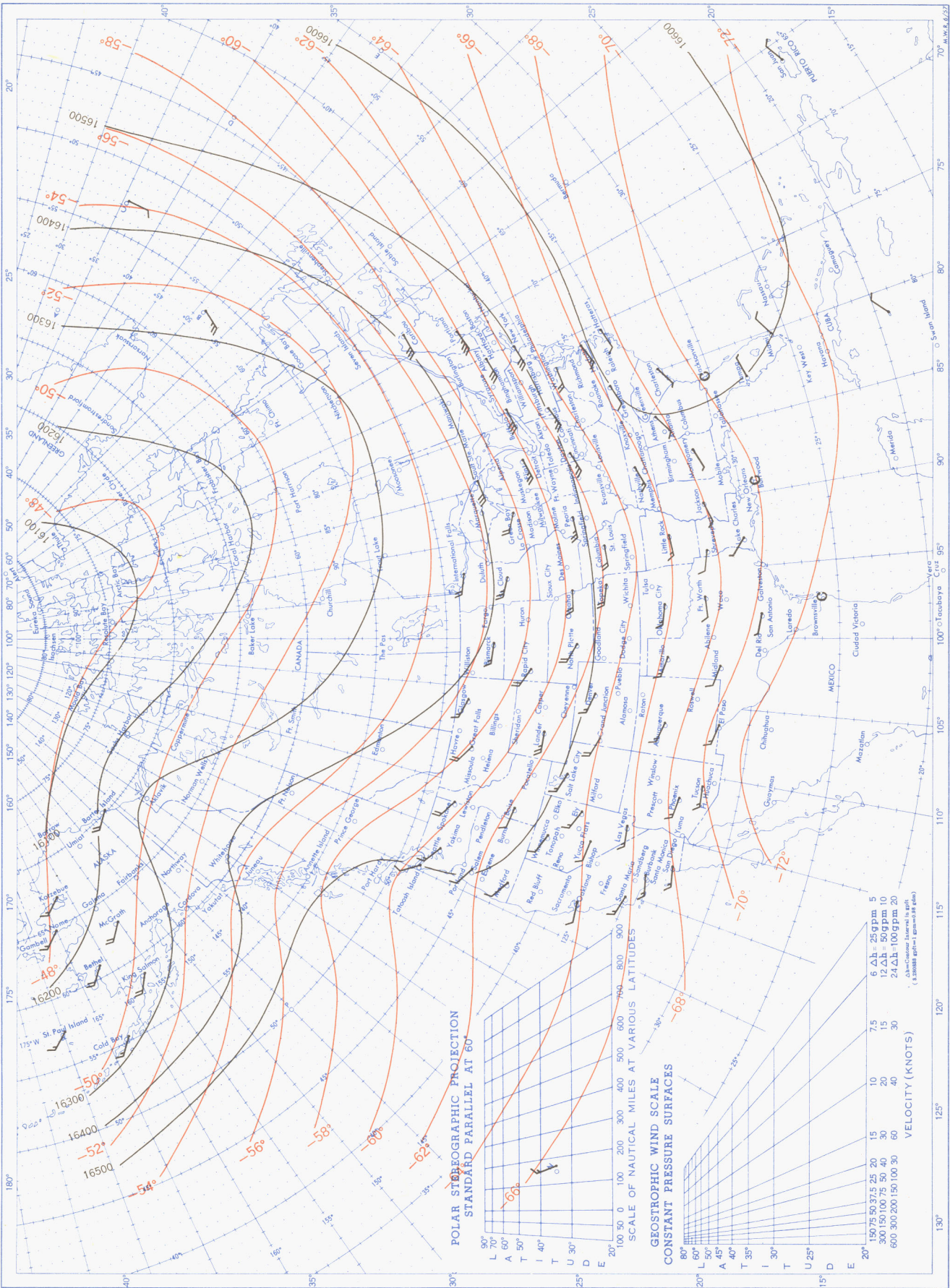
See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 1200 GMT, September 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.

Chart XVII. 100-mb. Surface, 1200 GMT, September 1957. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map.